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AN ANALYSIS OF ESTIMATED VALUES OF MAXIMUM USABLE FREQUENCY THROUGHOUT A SUNSPOT CYCLE AND ASSOCIATED ELECTRON DENSITY TRENDS, AT CHRISTCHURCH, NEW ZEALAND

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Abstract

A method of deriving tables of sunspot cycle changes in hourly values of maximum usable frequencies from basic vertical sounding ionosphere data is described, and the technique developed for construction of virtual height curves, representative of median conditions, for a rapid computation of M factors for distances shorter than the standard 3000 kilometres is outlined.

Some of the factors affecting accuracy of tables are critically examined. The linear relationship assumed between increase in foF2 and increase in running average sunspot number is observed to degenerate markedly as the high sunspot numbers of the 1957–58 maximum are reached. As this effect is particularly significant during daylight hours, ion density changes at noon L.M.T. are investigated and associated trends in true heights are also considered in an endeavour to determine possible causes of ion density loss. The evidence points to a temperature effect.

Seasonal variation in noon maxima of foF2 throughout the sunspot cycle examined is found to oscillate from summer maxima at sunspot minimum through a period of equinoctial maxima with the rising cycle to winter maxima (the winter anomaly expected at temperate latitudes) near sunspot maximum. Approximations to ion densities and true heights for different seasons at these varying stages of the cycle are examined and reference made to the possible contribution of physical processes such as mixing of atmospheric gases and changes in temperature.

Ratios of disturbance to calm day ion densities, examined seasonally and at different stages of the sunspot cycle, show pronounced seasonal and sunspot cycle variations and reveal large equinoctial and summer daytime departures. It is suggested that these are due to atmospheric mixing of gases resulting in ion density loss through an attachment-like process. The significance of increased F-layer stratification during disturbance is discussed.

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INTRODUCTION

Tables of sunspot cycle changes in hourly values of maximum usable frequencies (MUF) for zero, 400, 800, and 3000 kilometre distances have been compiled from Lincoln and Godley Head (Christchurch) vertical sounding ionospheric data to assist in predicting frequency usage for internal New Zealand radio circuits. (Christchurch Geophysical Observatory *Bulletin,* 1960). In addition to supplying an estimation of median MUF values throughout a sunspot cycle, the tables also include representative calm and disturbed values for the 800 and 3000 kilometre distances to indicate expected daily scatter about median conditions.

The basic problem involved in relating observed frequencies of reflection of radio waves at vertical incidence on the ionosphere, recorded on vertical sounding ionograms, to oblique incidence reflection frequencies, required for practical transmission purposes, has been solved with sufficient accuracy for present prediction requirements at mid-latitudes by the use of the following three well-known theorems:

(1) The secant law, which relates vertical and oblique frequencies reflected from the same true height by the formula $f_{ob} = f_v \sec \phi_o$ where f_v is the frequency at vertical incidence, f_{ob} is the frequency at oblique incidence, and ϕ_o is the angle of incidence on the layer;

(2) Breit and Tuve's (1926) theorem, which states that the time taken to traverse the actual curved transmission path at the group velocity is equal to the time needed to travel over the equivalent triangular path at the free space velocity;

(3) Martyn's (1935) theorem, which states that the virtual height for f_v is equal to the height of the equivalent triangular path for f_{ob}.

Direct scaling of f_v can be made from virtual height – frequency curves recorded on vertical sounding ionograms, and a graphical method of ionogram scaling of $\sec \phi_o$ corrected for earth and ionosphere curvature has become the standard technique for this parameter. This method was developed by Newburn Smith (1939) and basically involves plotting of $\log \sec \phi_o$ against virtual heights for the required transmission distance. In the degenerate case of zero distance, the "transmission curve" becomes a vertical straight line.

In practice, the scaling technique involves fitting a $\sec \phi_o$ transmission curve transparency for the appropriate distance to the ionogram height grid. At the point of tangency f_v can be read on the ionogram logarithmic frequency scale and its equivalent $\sec \phi_o$ on the transparency logarithmic scale, which is similar to the ionogram scale but in the reverse direction. From these two scalings the maximum value of f_{ob} can readily be deduced using the relationship (1) above.

Instead of scaling f_v and $\sec \phi_o$ it is usual in practice to scale the critical or penetration frequency of the layer and the M factor where

$$\text{M factor} = (\text{Maximum Usable Frequency})/(\text{Critical Frequency})$$

and is read on the M factor scale.

Scalings of the critical frequency of the F2 region (foF2) and the factor M3000F2 are part of the routine programme at any vertical sounding station as these parameters contribute to zonal MUF predictions on a world-wide scale. Lincoln and Godley Head (Christchurch) hourly values were available over the sunspot cycle interval 1947–58 for computing MUF's for the 3000 kilometre distance centred at Christchurch.

TECHNIQUES USED IN MUF ESTIMATION

Construction of MUF Tables for the 3000 Kilometre Distance

It is well known that the critical frequencies of the E, F1, and F2 layers show a substantially linear increase with increase in sunspot number. This relationship enables frequency forecasts over a sunspot cycle to be made with sufficient accuracy for practical use. In the present project the linear decrease of M factor with increase in sunspot number has also been taken into consideration to increase prediction accuracy.

For each hour of the day for each month of the year, foF2 median values 1947–58 were plotted against appropriate twelve-month running average Zurich relative sunspot number (RASSN) centred at mid-month. A linear least-squares fit was applied, although certain marked departures from linearity particularly in the daylight hours were observed. These departures will be referred to later in this paper. Median values of M3000F2 were treated in the same way, and median MUF 3000 values were obtained by scaling foF2 and M3000F2 from the linear fit at RASSN 0, 10, 20, . . . 200 and computing the product (Fig. 1 and Table 1).

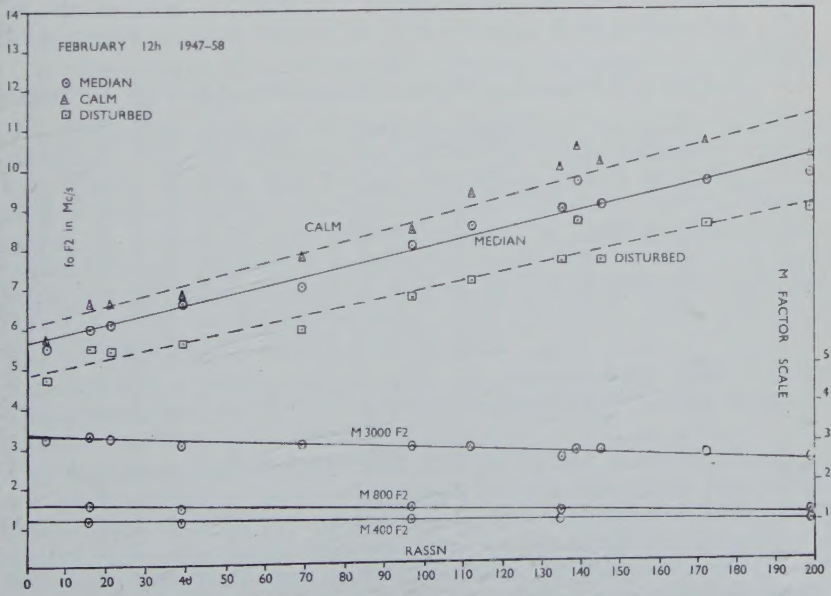


FIG. 1—Least-squares fits for FoF2 v RASSN and M factors v RASSN, 1947–58.

TABLE 1—Diurnal Variation of MUF 3000 Median Values for Christchurch, February 1947–58 (in Mc/s). Sunspot Numbers (RASSN) are 12-month Running Average Zurich Relative Sunspot Numbers (Provisional). M.M.T. 172·5° E.

RASSN	00h	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22	23
0	11·4	10·5	9·4	9·0	7·1	7·9	12·3	14·3	15·4	17·0	17·1	17·5	18·9	18·5	18·5	18·3	17·4	17·4	17·3	17·8	18·2	16·3	14·6	11·9
10	12·0	11·2	9·9	9·3	7·6	8·4	12·3	14·7	15·9	17·7	17·9	18·0	19·5	19·0	18·9	18·7	18·2	18·0	18·1	18·3	18·4	16·5	14·8	12·8
20	12·5	11·3	11·1	9·9	8·2	8·9	12·9	15·2	16·3	18·0	18·4	18·6	19·7	19·5	19·3	19·2	18·4	18·4	18·4	18·9	18·9	17·3	15·5	13·7
30	13·1	11·9	11·0	10·4	9·0	9·6	13·3	15·7	17·0	18·6	18·8	19·2	20·2	20·2	20·0	19·7	18·9	18·9	18·9	19·3	19·5	17·7	16·2	13·8
40	13·6	12·6	11·6	10·7	9·3	9·9	13·5	16·3	17·5	19·5	19·5	20·0	21·0	20·5	20·3	20·2	19·6	19·2	19·8	19·5	19·8	18·0	16·5	14·3
50	14·2	13·0	12·2	11·3	9·9	10·3	14·1	16·5	18·2	19·7	20·2	20·2	21·1	21·1	20·8	20·8	20·0	19·8	20·6	20·3	20·1	18·6	17·1	15·1
60	14·8	13·7	12·7	11·7	10·5	10·8	14·3	17·0	18·6	20·2	20·7	20·9	21·7	21·4	21·3	20·9	20·4	20·4	20·4	21·0	20·6	19·5	17·6	15·5
70	15·2	14·2	13·2	12·0	11·0	11·3	14·6	17·3	19·2	20·9	21·1	21·6	22·0	21·9	21·6	21·4	21·0	20·9	21·1	21·2	21·0	19·4	18·0	16·0
80	15·7	14·6	13·6	12·6	11·5	11·6	15·2	17·7	19·8	21·5	21·6	21·9	22·5	22·5	22·2	22·1	21·2	21·0	21·4	21·5	21·2	19·9	18·5	16·6
90	16·3	15·1	14·0	13·0	12·2	12·2	15·4	18·4	20·0	21·7	22·4	22·5	22·9	22·8	22·4	22·3	21·8	21·5	21·8	22·0	21·6	20·2	18·8	17·3
100	16·6	15·6	14·6	13·3	12·5	12·5	15·6	18·5	20·7	22·4	22·7	22·9	23·2	23·2	22·9	22·6	22·3	22·3	22·5	22·9	22·1	20·5	19·2	17·6
110	17·0	16·2	15·0	13·8	13·0	12·9	16·2	18·9	21·3	23·1	23·2	23·8	23·7	23·8	23·2	22·9	22·4	22·4	22·8	23·1	22·3	21·0	19·7	18·1
120	17·7	16·4	15·3	13·9	13·5	13·4	16·1	19·5	21·8	23·3	23·8	23·9	23·9	23·7	23·6	23·2	22·7	22·7	23·0	23·2	22·4	21·4	20·0	18·7
130	18·0	17·0	15·9	14·4	13·8	13·7	16·5	19·8	22·4	23·6	24·4	24·5	24·4	24·4	24·1	23·8	23·5	20·4	23·7	23·8	23·0	21·5	20·3	19·2
140	18·3	17·5	16·2	15·1	14·3	14·0	17·1	20·0	22·8	24·4	24·8	24·9	24·7	24·5	24·4	23·9	23·7	23·4	23·9	24·6	23·3	21·8	21·0	19·6
150	18·8	17·7	16·5	15·2	14·8	14·6	17·0	20·6	23·2	24·9	25·1	25·6	24·7	24·6	24·5	24·3	23·8	23·9	24·2	24·8	23·3	22·6	21·2	20·0
160	19·3	18·3	17·0	15·5	15·3	14·7	17·4	20·6	23·8	25·5	25·7	26·1	25·3	25·2	25·1	24·8	24·4	24·3	24·7	24·8	23·7	22·7	21·4	20·5
170	19·5	18·4	17·4	16·0	15·0	15·1	17·8	21·0	24·4	25·8	26·3	26·5	25·4	25·5	25·4	24·7	24·9	24·8	25·2	25·5	24·2	22·8	22·0	21·1
180	19·9	18·9	17·5	16·2	16·1	15·6	18·0	21·4	24·8	26·0	27·1	27·0	25·5	25·6	25·5	25·1	24·8	24·8	25·2	26·2	24·2	23·4	21·9	21·5
190	20·5	19·2	18·0	16·3	16·3	15·7	18·1	21·5	25·3	26·7	27·2	27·8	26·2	26·0	25·9	25·5	25·3	25·2	25·7	26·2	24·4	23·7	22·3	21·9
200	21·1	19·5	18·3	16·8	16·7	16·0	18·6	21·9	25·8	27·4	27·5	28·0	26·3	26·0	26·2	25·7	25·8	25·6	26·3	26·6	24·8	23·5	22·8	22·1

Median MUF values did not appear entirely adequate for a full description of conditions possible in any one month, as foF2 in particular can show considerable departures from normal conditions during ionospheric storms. Hence, in order to supply some indication of expected scatter about median values, five calm days and five disturbed days were selected for each month by means of an I Index (Bullen, 1952), a three-hourly index emphasizing storm departures from normal conditions reflected in decreases in foF2 and increases in F2 virtual heights. Mean values of foF2 for quiet and disturbed conditions were obtained from the data for each month and plotted against RASSN. As before least-squares fits were applied to the foF2 data and tables prepared for mean calm and disturbed MUF 3000 values. Computations were made using the original M3000 fit, which was not greatly altered by disturbance conditions (Fig. 1).

Technique for Shorter Distances

For greatest accuracy at very short transmission distances scaling of MUF values from the ordinary trace is not considered adequate as the relation of the path to the earth's magnetic field must be taken into consideration. The correction for this effect is complex, except in the limiting case of vertical incidence sky-wave transmission for zero distance. In this case MUF 0 is taken as the extraordinary wave critical frequency, which includes the effect of the earth's magnetic field.

To evaluate MUF's for the distances 400 and 800 kilometres it was essential either to find a direct empirical relationship between M factors for the required distances and M factors for the 3000 kilometre distance or to evolve a speedy method of direct scaling of M factors.

As the distance factor technique produced too great a variability in results for the required accuracy a method was evolved as follows:

A normalised curve for a particular hour of a particular month was constructed using the information supplied by median parameters obtained from routine scalings, and Booker and Seaton (1940) theoretical virtual height–frequency curves were fitted to these. Booker and Seaton theoretical curves are constructed for parabolic regions of different semi-thickness having the same penetration frequency and with their maxima at the same height hm where hm is scaled at ·834 of the critical frequency. The parameters used to fix the experimental curve were foF2, h′F2, foF1, h′F, h′pF2 (height at ·834 FoF2) and M3000F2.

In this way a unique median curve was obtained from which a scaling could be made of an M factor for any required distance using the appropriate sec ϕ_o transmission curve (Fig. 2).

As the change of M factor with RASSN for the shorter distances was not great, normalised curves were found for only five or six years of the twelve years investigated, appropriately spaced according to place in the sunspot cycle. A straight line was fitted as for M3000F2 and tables of MUF 800 computed from foF2 and M800 factors at RASSN 0, 10, 20, . . . 200. Tables of calm and disturbed values were also included for this distance (Fig. 1).

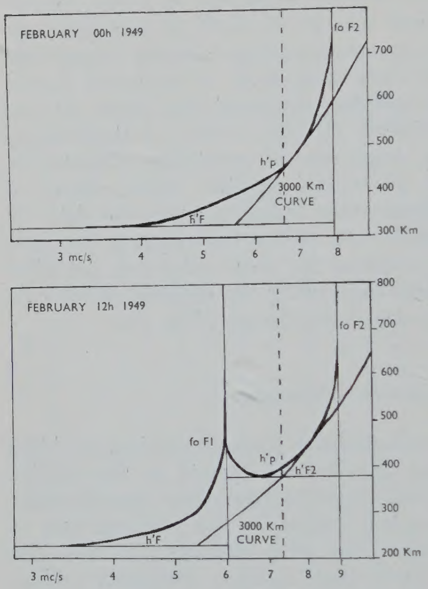


FIG. 2

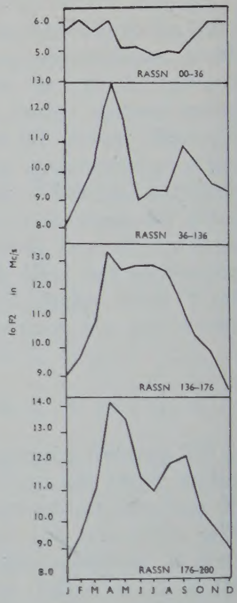


FIG. 4

FIG. 2—Representative median curves constructed from routine parameters, scaled for the 3000 km distance, and Booker and Seaton theoretical virtual height–frequency curves.

FIG. 4—Seasonal variation of noon values of foF2 throughout a sunspot cycle.

The same method was applied to the 400 kilometre distance, but because of the shortness of this distance the effect of the earth's magnetic field was considered in addition. Newburn Smith's (1939) method of including an approximate correction for this effect was applied.

ANALYSIS OF DATA AND RESULTS

Accuracy of Median Value Tables

Standard deviations about the regression of foF2 on RASSN in mc/s and correlation coefficients resulting from correlation of foF2 with RASSN are listed in Table 2 for local midnight and noon. High correlation coefficients and small standard errors indicate that the linear fit is a satisfactory representation of the trend of median foF2 values with increasing RASSN and confirms the reliability of the method used in constructing the tables.

Standard deviation about the regression of M factors on RASSN was also examined but found to be of negligible significance. Errors in MUF median tables then are almost entirely due to foF2 departures from the least-squares fits and vary according to the value of M factor appropriate to the distance. Table 3 supplies an approximation to MUF errors for each month at midnight and noon for the four distances covered in the survey. These errors apply to median departures only and not to daily fluctuations.

TABLE 2—Correlation of foF2 with Running Average Sunspot Number (RASSN), Christchurch, 1947–58. M.M.T. 172·5° E.

——		Number Observations	Standard Deviation about Regression on RASSN (Mc/s)		Correlation Coefficient	
			00h 00m	12h 00m	00h 00m	12h 00m
January	S	12	0·335	0·478	0·973	0·924
February	S	12	0·424	0·226	0·965	0·987
March	E	12	0·442	0·686	0·962	0·953
April	E	12	0·259	0·771	0·988	0·971
May	W	11	0·432	0·754	0·949	0·969
June	W	11	0·410	0·799	0·902	0·957
July	W	11	0·300	0·797	0·957	0·957
August	W	12	0·285	0·769	0·978	0·960
September	E	12	0·516	0·826	0·965	0·950
October	E	12	0·439	0·638	0.969	0·949
November	S	12	0·364	0·425	0.965	0·953
December	S	12	0·504	0·583	0.930	0·867

S = Summer E = Equinox W = Winter

There is, in addition, the daily fluctuation about the monthly median to be considered. Some indication of scatter due to this has been supplied in the tables of calm and disturbed day values for the 800 and 3000 kilometre distances, and Table 4 is included to provide a similar estimation for the zero and 400 kilometre distances. Mean hourly disturbance departures in foF2 (calm – disturbed) in mc/s at different seasons are tabled for sunspot maximum and sunspot minimum. It will readily be seen that disturbance departures of foF2 during the night hours are relatively small on the average but a significant change occurs during daylight hours particularly at sunspot maximum and in the equinoctial months. From the practical point of view Table 4 supplies an approximation to average disturbance departures for zero MUF, and when hourly values are multiplied by M factor 1·1 approximations to MUF 400 mean disturbance departures are obtained.

Discussion

Statistical tests have indicated that the techniques used in estimation of median values of maximum usable frequencies throughout a sunspot cycle from Christchurch foF2 and M factor information have produced results with a good degree of reliability for practical use. The inclusion of calm and disturbed MUF tables supporting median estimates has supplied a needed indication of daily scatter.

TABLE 3—Approximate Limits of Error in Median MUF Tables in Mc/s.

	MUF 0	MUF 0	MUF 400	MUF 400	MUF 800	MUF 800	MUF 3000	MUF 3000
	00h 00m	12h 00m	00 00	12 00	00 00	12 00	00 00	12 00
January	±0·3	±0·5	±0·4	±0·5	±0·4	±0·6	±0·9	±1·3
February	±0·4	±0·2	±0·5	±0·3	±0·5	±0·3	±1·1	±0·7
March	±0·4	±0·7	±0·3	±0·8	±0·6	±1·0	±1·2	±2·0
April	±0·3	±0·8	±0·5	±0·8	±0·3	±1·1	±0·7	±2·3
May	±0·4	±0·8	±0·4	±0·8	±0·6	±1·1	±1·2	±2·4
June	±0·4	±0·8	±0·3	±0·9	±0·5	±1·2	±1·2	±2·6
July	±0·3	±0·8	±0·3	±0·9	±0·4	±1·2	±0·8	±2·6
August	±0·3	±0·8	±0·3	±0·9	±0·4	±1·1	±0·8	±2·4
September	±0·5	±0·8	±0·6	±0·9	±0·7	±1·2	±1·4	±2·5
October	±0·4	±0·6	±0·5	±0·7	±0·5	±0·9	±1·2	±1·8
November	±0·4	±0·4	±0·4	±0·5	±0·5	±0·6	±1·0	±1·2
December	±0·5	±0·6	±0·5	±0·6	±0·6	±0·8	±1·3	±1·6

TABLE 4—Mean Hourly Disturbance Departures foF2 in Mc/s at Different Seasons

Sunspot Minimum 1950–55

	00h	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22	23
Summer	1·0	0·8	1·1	1·2	1·0	1·0	1·1	1·3	1·5	1·6	1·5	1·4	1·4	1·4	1·2	1·1	1·2	1·1	1·1	1·1	1·0	1·1	1·0	1·0
Equinox	1·0	0·9	0·9	0·8	0·9	0·7	0·9	1·2	1·4	1·5	1·8	1·8	1·8	1·8	1·8	1·7	1·4	1·4	1·4	1·3	1·1	1·2	1·2	1·1
Winter	0·6	0·8	0·9	0·9	0·9	0·8	0·8	0·8	1·0	1·2	1·3	1·3	1·2	1·3	1·2	1·1	1·0	1·1	1·0	0·9	1·0	0·8	0·8	0·7

Sunspot Maximum 1947–49 : 1956–58

	00h	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22	23
Summer	1·1	1·1	1·2	1·2	1·2	1·4	1·8	2·2	2·4	2·4	2·3	2·2	2·1	2·0	1·9	1·8	1·7	1·6	1·5	1·4	1·3	1·1	1·2	1·2
Equinox	1·3	1·3	1·5	1·5	1·4	1·5	1·6	2·5	3·3	3·9	4·0	3·6	3·4	3·0	2·8	2·6	2·4	2·3	2·1	1·9	1·5	1·6	1·6	1·4
Winter	1·1	1·2	1·1	1·3	1·2	1·1	1·0	1·3	1·6	1·9	2·1	1·8	1·6	1·5	1·4	1·4	1·6	1·6	1·4	1·4	1·4	1·3	1·3	1·1

It would appear that this type of statistical method has reached its limit and any improvements in MUF estimation are dependent on an increased understanding of the physical processes underlying changing behaviour patterns in F-region maximum ion densities and true heights throughout a sunspot cycle during both quiet and disturbed conditions.

PHYSICAL FACTORS AFFECTING MUF ESTIMATION

In the latter part of this paper some of the variable physical factors affecting the techniques used in MUF estimation are examined. A quantitative investigation of the physical processes involved is beyond the scope of this survey, which aims mainly at indicating significant ion density and height trends occurring in the sunspot cycle analysed and suggesting from the accumulated evidence possible physical conditions contributing to the observed effects.

Departure from Linear Relationship of foF2 and RASSN

The linear relationship assumed to hold between increases in foF2 and RASSN was observed to degenerate markedly as the high sunspot numbers of the 1957–58 maximum were reached, the values of foF2 observed at this stage of the cycle being considerably less than expectation from the linear trend of earlier observations. In order to examine this anomaly more critically, with seasonal variations eliminated, twelve-month running average monthly median values of foF2 for noon and midnight were plotted against RASSN. While small departures from linearity were apparent for lower sunspot numbers, above RASSN 170 little increase of foF2 with RASSN occurred.

This pronounced departure from the linear trend at the 1957–58 maximum has also been observed by Chun-Ming Huang (1960) at a number of vertical sounding stations in the Western Pacific area. These stations indicate both a diurnal and latitude variation in the time of onset of the phenomenon relative to sunspot number and in the amplitude of departure from linearity.

In an endeavour to establish a possible cause for ion density loss at high RASSN suggested by the foF2 relative decrease, trends of maximum F2 ion densities (Nm), where $\mathrm{Nm} = (1.24 \times 10^4)\ \mathrm{foF2}^2$ e/cc, were examined for the period 1954–58. Noon values only were utilised as the effect was more marked in the daylight hours. The ion density departure from linear trend above RASSN 170 was clearly defined for median, calm, and disturbed conditions (Fig. 3).

If it is assumed that the noon F2 maximum ion density at a fixed pressure level is an approximation to the equilibrium value $N = q/\beta$, where q is the rate of ion production and β is the rate of loss by an attachment-like process, then the linear increase of N with RASSN, neglecting height changes and changes in β, could be explained in terms of an increase in q due to an increase in incident ionizing radiation of the order of 4:1 for calm conditions. However, other factors need to be considered in addition, and the significance of height changes throughout the cycle, indicative of temperature and scale-height variations, were next examined.

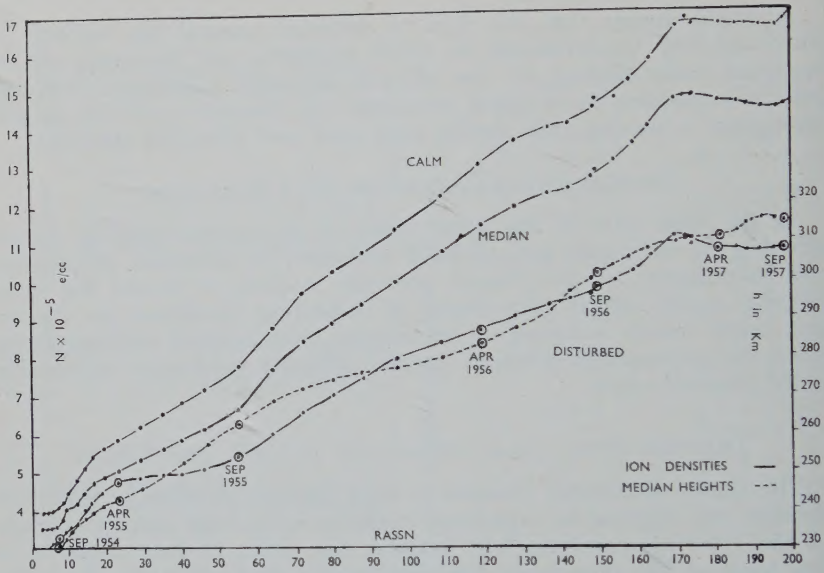


FIG. 3—12-month running averages of N max v RASSN 1954–58 showing non-linearity above RASSN 170 and annual residual variation.

A reasonable coverage of representative calm-day true height values of h max for noon 1954–58 were readily available from N′h profiles calculated by Cummack using King's (1956) method of N′h analysis. It was thus possible to examine approximate trends of twelve-month running average noon h max values for the 1954–58 interval. Where the coverage was not complete, a relatively quick computation of h max was made using King's (1960) median trace method combined with a slider technique. These latter values did not depart significantly for this purpose from the more rigorous calm day computations. From Fig. 3 it will be seen that the plotted height trend coincided with the disturbed ion-density trend. As this latter exhibited similar departures from linearity to the median and calm ion-density trends, it was taken as the ion-density standard of reference for comparison purposes.

In the following discussion it is assumed that height increases are indicative of increased temperatures and scale heights (H); and that an increase in H can result in a reduction in q, as $qH \propto I$ where I is the incident ionizing radiation.

Fig. 3 shows that for the years 1954–56 there remains a residual annual variation after elimination of the main seasonal trend has been effected by the smoothing process. For these years a relative height minimum and ion-density maximum centres round April and a relative height maximum and ion-density minimum centres round September. To ascertain the conditions contributing to this effect the method of smoothing was examined, and it was obvious that in any year the twelve-month running averages for April and September both included the equinoctial and winter months

April to October. The April average in addition included the effect of the preceding summer months, November to March, while the September average included the effect of the following summer months. As the rising phase of the sunspot cycle was examined, it is tentatively suggested at this stage that an increase of temperature from sunspot minimum to sunspot maximum could effect a relative decrease in ion densities for each succeeding summer. An examination of the declining phase of the cycle confirmed the conclusion that the summers nearer sunspot maximum are characterized by greater relative ion-density loss than those nearer the minimum, as the height and ion-density departures for April and September were found to reverse on the downward trend.

Above RASSN 170 the height trend seemed to be maintained for a time after the linear increase in ion density had ceased to be effective. It is postulated that critical increases in scale height occurring at all seasons from the 1956–7 summer season onwards have been sufficiently large to offset the increase in q due to an increasing incident ionizing radiation. The effect of increased storm incidence was also taken into account, but the evidence weighed in favour of the temperature effect mentioned above because the ion-density departures were similar under both calm and disturbed conditions (Fig. 3).

Seasonal Variations throughout a Sunspot Cycle

In order to investigate significant seasonal changes in ion-density trends throughout the cycle more fully, the months of the year were grouped seasonally as follows:

Summer: January, February, November, December
Equinox: March, April, September, October
Winter: May, June, July, August

Seasonal midnight values behaved according to expectation, attaining summer maxima and winter minima throughout the cycle, while noon values demonstrated the expected temperate latitude anomaly of winter daytime maxima near sunspot maximum. However, at Christchurch this anomaly did not extend through to sunspot minimum.

From RASSN 00–36 noon summer maxima occurred with winter minima. This set of conditions was replaced from RASSN 36–136 by equinoctial maxima, summer minima, and secondary winter minima. The winter anomaly appeared from RASSN 136–176, while for the higher RASSN 176–200 in the year 1958 there was a return to pre-winter anomaly conditions, which are an equinoctial maximum, a summer minimum, and a secondary winter minimum.

This changing behaviour pattern in noon values of foF2 was found to be generally typical of the daylight hours and was associated with changing patterns of F-layer stratification and with seasonal height changes at different stages of the cycle.

Rishbeth and Setty (1961) have suggested that the winter anomaly in the F2 layer is associated with changes in composition in the upper atmosphere, which alter the ratio of concentrations of O (atomic oxygen) effective in absorbing solar ultraviolet radiation, and N_2 (molecular nitrogen) responsible for loss of ions in the F2 region by a linear law attachment-like process. These authors suggest that complete mixing of these gases might increase the concentration of N_2 in summer, thus increasing F2 loss rate for this season, while diffusive separation in winter would result in a decrease of loss by attachment and possibly also an increase in rate of production because of an increased relative concentration of O.

The evidence in this survey indicates that such atmospheric mixing is probably a contributing factor to the observed trends, and that F1-layer formation is in part associated with this process. As there appears to be a height factor involved also, Table 5 is provided to give an approximation to mean true heights and calm-day ion densities at noon for different phases of the sunspot cycle.

TABLE 5—Approximations to Noon Values of Mean True Heights and Calm-Day Ion Densities at Different Phases of the Sunspot Cycle

RASSN	Summer		Equinox		Winter	
	h max	N max	h max	N max	h max	N max
	Km.	$N \times 10^{-5}$e/cc	Km.	$N \times 10^{-5}$e/cc	Km.	$N \times 10^{-5}$e/cc
00–36	235	4·9	235	4·9	225	3·9
36–136	290	9·2	275	12·2	260	9·2
136–176	330	11·9	305	17·6	270	18·2
176–200	345	12·2	315	19·7	280	19·4

From Table 5 it will be seen that at sunspot minimum (RASSN 00–36) there is little significant seasonal change in height so that a marked seasonal temperature difference is not likely. Stratification of the F region into F1 and F2 occurs at all seasons during the daylight hours, though it is more complete in summer and equinox than in winter. Although the solar zenith angle χ is highly significant in the formation of the F layer, as indicated by Chapman (1931) theory, the ratio of summer to winter maximum ion densities at this stage of the cycle is less than would be expected if χ were the sole factor contributing to differences in F-region behaviour. It therefore appears likely that atmospheric mixing is also significant in producing infinite F1 cusps and in decreasing N max in the summer months through increased rate of attachment. At sunspot minimum the summer ion-density loss through this means is not sufficient to offset the greater rate of ion production due to more steeply incident radiation. Hence the summer maximum is maintained.

From RASSN 36–136, Table 5 indicates an increase in noon h max at all seasons with summer averages reaching approximately 290 km, which is much higher than h max for equinox and winter. In addition a decrease in incidence of F1-layer formation is apparent with increase in height at all seasons, the incidence of stratification being considerably less for equinox and winter than for summer. Increased scale heights and relatively increased attachment rate due to greater heating and mixing during the summer months thus can both contribute to ion-density loss during the summer season, with equinox and winter maintaining their former relative status.

At the later stage of the cycle, RASSN 136–176, a large increase in equinoctial noon h max (approximate average 305 km) relative to winter (approximate average 270 km) appears to reflect increasing equinoctial scale heights and thus reduces the rate of ion production relative to the winter months. The ion-density gain in winter relative to equinox at this stage of the cycle is lost above RASSN 176 when winter heights also increase to a critical level. At this stage of the cycle, stratification during quiet conditions has been still further reduced but remains a significant factor for the summer season.

These indications of relative seasonal ion-density loss due to changing conditions of atmospheric mixing and scale-height variations are based mainly on qualitative judgment, but the evidence suggests strongly that these are the main physical processes involved.

Sunspot Cycle Changes in Diurnal Trends of Ionospheric Storm Departures

Appleton and Piggott (1952) examined the diurnal trend of ratios foF2D/foF2Q, where D indicates disturbed and Q quiet conditions, for each hour of the local day at Washington for the years 1945 and 1949, and they noted that the maximum relative departure of foF2 from its quiet-day value was reached before noon on disturbed days, the plotted trend indicating maximum departure at 8 h. L.M.T.

In an analysis of disturbance conditions at Christchurch, the ratio of D/Q values of N max were examined during summer, winter, and equinox at the four stages of the sunspot cycle referred to in the previous section. It was immediately evident that both seasonal and sunspot-cycle changes existed in the D/Q ion-density variations (Fig. 5).

The most spectacular daytime disturbance departures occurred during the equinoctial months particularly at sunspot maximum where, at equinox, calm-day conditions, similar to those for winter with little tendency to F1-layer formation, were replaced during storms by disturbed conditions, similar to those for summer, with pronounced F-layer stratification (Fig. 6).

An examination of storm ionograms indicated that an increased tendency to stratification at all seasons during the daylight hours was associated with decreases in foF2 and consequently in N max. During equinox and summer this tendency was apparent for all major storms, while in winter only the rare great storm was effective in producing this result to any marked degree. The storm phenomenon, then, appears to be closely related to mixing of atmospheric gases, resulting in an increased concentration of N_2 and consequent loss of ions by attachment processes at the ion-density maximum of the F2 region. There seems little evidence of increased values of h max during the daylight hours except perhaps at equinox, and so if a temperature effect is present it does not appear to be the major factor.

It is considered that atmospheric mixing during storms may be brought about by the onset of a train of neutral gaseous waves (Wright, 1961) of large amplitude originating in the auroral zone.

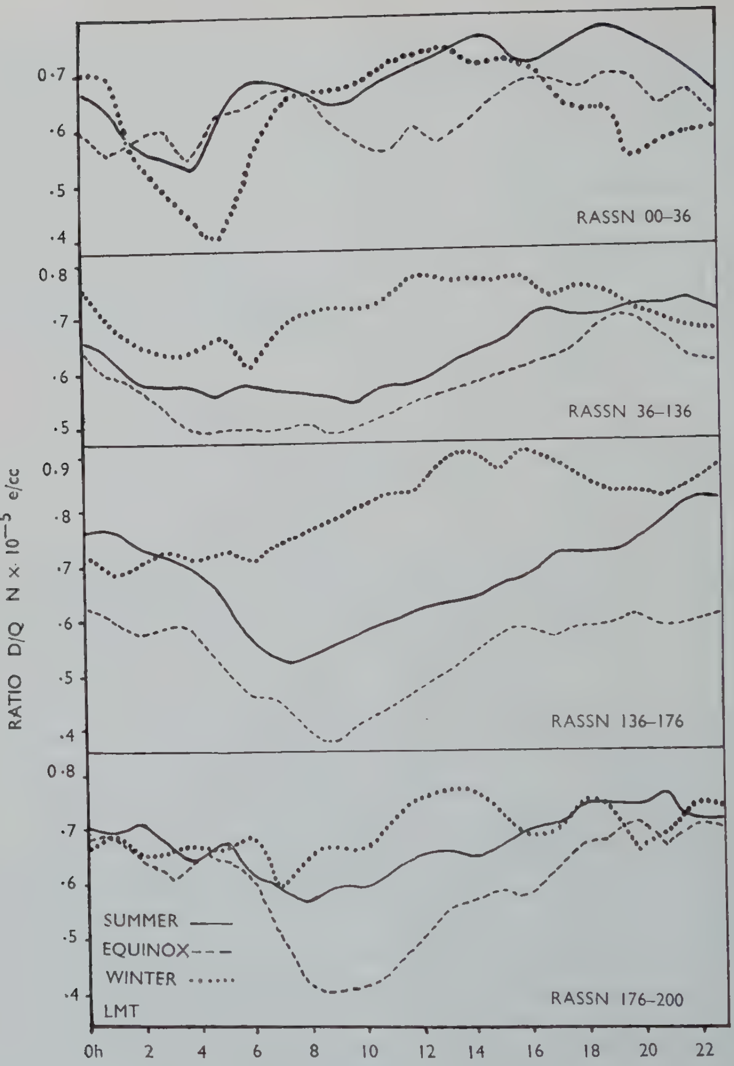
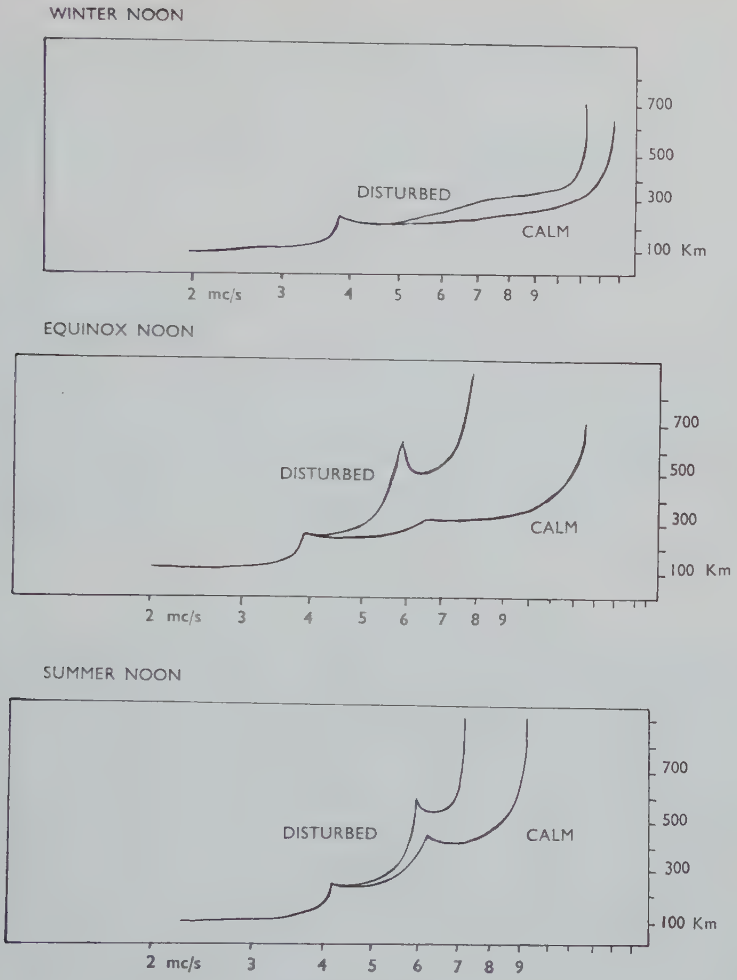


FIG. 5—Seasonal variation of D/Q N max.

From Fig. 5 it will be seen that at sunspot minimum (RASSN 00–36), when there is evidence of F1-layer formation at all seasons during quiet daylight conditions, and storm activity is less intense, the winter pattern D/Q is similar to the calm-day trend. This description applies also to summer storm variation in the main, but greater relative density loss is clearly indicated at this season at 6–9h and again at 16–19h L.M.T. At these times sharp F1 cusps during quiet conditions are replaced by infinite F1 cusps during disturbed conditions, suggesting the effect of relatively



WINTER NOON

EQUINOX NOON

SUMMER NOON

FIG. 6—Seasonal disturbance changes at noon in foF2 and F-layer stratification at sunspot maximum.

increased atmospheric mixing and consequent greater loss through attachment. From 10–15h loss by attachment is already high during quiet conditions, as indicated by infinite foF1 and a dip in the quiet-day N max trend. The ion-density loss due to disturbance at this stage of the cycle is most pronounced at equinox between 8 and 16h L.M.T., when infinite F1 cusps occur during disturbance replacing non-infinite quiet-day F1 cusps. At midday where infinite foF1 can occur during quiet conditions at this season the disturbance departure is relatively less (Fig. 6).

At later stages of the cycle, particularly above RASSN 136, daytime disturbance departures, more particularly for summer and equinox, are at a maximum from 6 to 10h L.M.T., the maximum summer departure occurring at 8h, in agreement with the findings of Appleton and Piggott (1952), and for equinox at 9h. These times coincide with the maximum of occurrence of the storm G condition for these seasons where the F2 region has been completely lost through attachment processes and spectacular examples of infinite foF1 occur. As the day progresses, apart from the most severe storms, this condition is overcome by increase in rate of ion production by incoming radiation.

Discussion

This survey has indicated qualitatively that atmospheric mixing processes and temperature variations. as well as changes in rate of ion production due to the effect of varying incident ionizing radiation, are significant in producing changing behaviour patterns in maximum ion densities throughout a sunspot cycle. A full quantitative supporting analysis is required to confirm the suggestions made.

Greater insight into basic movements of the atmosphere, capable of producing mixing of the atmospheric gases involved, is also needed to increase understanding of the variations observed.

ACKNOWLEDGMENTS

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SOME ANALYSED ROCKS FROM WESTLAND, NEW ZEALAND

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Abstract

Chemical and mineralogical compositions are given for biotite hornfels from the Paringa River, greywacke from near Waiho, and hornblende gabbro, tinguaite, and camptonite from the Haast Valley.

INTRODUCTION

During a survey of the metamorphic rocks of the Southern Alps other rock types were examined and collected. Five of these have been chemically analysed. The chemical analyses are given here (Table 1), and brief descriptions of the mineralogical composition and mode of occurrence of these rocks follow.

DESCRIPTION OF ROCKS

Biotite Hornfels (Table 1, No. 1)

The north abutment of the Paringa River road bridge is anchored to this rock, which is shown as Pre-Cambrian or Lower Paleozoic greywacke on the geological map of Wellman (1955). A contact against granite is shown on this map about 30 chains downstream. In fresh outcrop the hornfels is reddish-brown with a marked quartzitic lustre; it is very hard and tough, and breaks with an irregular blocky fracture.

In thin section the following minerals were recognised: quartz, in irregular, generally equidimensional grains, 0·1–0·5 mm in diameter; biotite, lath-shaped crystals 0·1–0·2 mm long, pleochroic from pale yellow to pale brown, sometimes chloritized; muscovite, in crystals like biotite, and frequently associated or intergrown with that mineral; clinozoisite, colourless rounded granules with strong relief, 0·05–0·1 mm in diameter; feldspar (probably a potash-soda feldspar), in rounded grains about 0·1 mm in diameter, pale grey and turbid from alteration products (sericite or kaolinite). The rock is interlaced with sparse veinlets of prehnite, about 0·2 mm in width. An estimated mode is: quartz, 60%; biotite, 12%; muscovite, 14%; feldspar, 7%; clinozoisite, 6%; prehnite, 1%. The texture is typically granoblastic. The density of the rock is 2·71.

The chemical composition of this rock, when plotted on the Q-L-M diagram of Reed (1957, Fig. 13), falls in the restricted field of Waiuta and Greenland Group greywackes. The analysis is comparable with that of a greywacke from Black Point Road, Reefton (Reed, 1957, Table 1, No. 17), except that the Paringa hornfels is notably low in sodium—in fact the sodium content is lower than any other analysed greywacke from New Zealand except one from Flat Creek, Mt Rangitoto (Reed, 1957, Table 1, No. 21).

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Greywacke (Table 1, No. 2)

This rock was collected from a fresh exposure at the abutment of the road bridge over a small stream locally known as Smithy's Creek, half a mile south of Docherty Creek on the Waiho-Weheka road. This is west of the Alpine Fault, and the rock is mapped as Devonian to Ordovician (Greenland Group) on the 1947 geological map of New Zealand.

Table 1—Analyses of Rocks from Westland (Analyst, Miss M. G. Speer)

	1	2	3	4	5
SiO_2	76·6	67·7	48·6	52·8	36·2
Al_2O_3	10·6	15·1	9·4	19·2	6·7
Fe_2O_3	0·50	1·75	2·05	3·30	7·00
FeO	2·40	2·25	9·00	0·80	5·30
MgO	1·90	1·55	9·90	1·40	14·60
CaO	1·90	2·30	12·10	1·70	12·90
Na_2O	0·50	4·60	2·60	11·20	1·30
K_2O	2·95	2·00	1·00	4·20	1·25
H_2O+	1·74	1·72	1·12	2·38	3·12
H_2O-	0·18	0·20	0·08	0·16	0·10
TiO_2	0·35	0·80	3·15	0·65	3·25
P_2O_5	n.f.	0·01	0·40	0·09	1·35
MnO	0·04	0·09	0·05	0·01	n.f.
CO_2	n.f.	0·10	0·06	1·05	7·0
Cl	—	—	—	0·30	—
Total	99·66	100·17	99·51	99·24	100·07

1. Biotite hornfels, Weheka-Haast road, at north end of Paringa River bridge. (P22191).*
2. Greywacke (Greenland Series), Waiho-Weheka road, half-mile south of Docherty Creek. (P22202).
3. Hornblende gabbro, Mossy Creek, 17 miles from Haast on the Haast- Makarora road. (P22234).
4. Tinguaite, Haast-Makarora road, 1 mile south of Clarke Bluff. (P22274).
5. Camptonite, Macpherson Creek, 20 miles from Haast on the Haast-Makarora road. (P23680).

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*Numbers refer to specimens deposited in the collections of the New Zealand Geological Survey.

This rock was selected for analysis because it appeared to show less metamorphism than other rocks of this group, most of which have been converted to hornfels, similar to that described above, by contact metamorphism. In hand specimen it is a tough, grey, fine-grained sandstone showing traces of shearing, which give it a faintly marked schistosity. However, a thin section shows that the rock is largely recrystallized. The following minerals were recognised: quartz, in irregular, generally equidimensional grains, averaging about 0·1 mm in diameter, but occasionally up to 0·5 mm; albite, in grains similar to quartz in size and appearance, but generally slightly turbid and sometimes showing polysynthetic twinning; muscovite (sericite), in tiny laths seldom more than 0·03 mm long; stilpnomelane, pleochroic from pale yellow to dark grey-green, in aggregates of blades up to 0·1 mm long; pumpellyite, in tiny (0·01 – 0·03 mm) grains and prisms with strong relief and low birefringence; clinozoisite, rounded granules 0·05 – 0·1 mm in diameter, grey and turbid from inclusions; a little opaque material; and rare grains of calcite. An estimated mode is: albite, 40%; quartz, 30%; muscovite, 15%; pumpellyite, 6%; stilpnomelane, 5%; clinozoisite, 4%. The density of the rock is 2·72.

This rock belongs to the chlorite zone of regional metamorphism, and in terms of the usual subdivision of this zone would be described as a chlorite 2 subzone greywacke.

The chemical composition of this rock, when plotted on the Q-L-M diagram of Reed (1957), falls in the field of the Lower Mesozoic "Alpine" greywackes, not in the field of Waiuta and Greenland Group greywackes. The analysis is comparable with those of greywackes from Gorge Hill, Waimakariri River (Reed, 1957, Table 1, No. 10) and from Mt Ida, Naseby Subdivision (Reed, 1957, Table 1, No. 14). Previously analysed greywackes from the Greenland Group are much higher in quartz than this one.

A conflict thus exists between the regional geology, which would place this greywacke in the Greenland Group, and the chemical composition, which indicates that the rock is closely related in composition to the Lower Mesozoic greywackes. Comparatively few Greenland Group greywackes have been analysed, however, and in view of the wide area over which they occur, the composition pattern as at present known may not be statistically valid.

Hornblende Gabbro (Table 1, No. 3)

This rock was found as boulders in Mossy Creek, a small stream that crosses the Haast-Makarora road near the 17-mile peg from Haast. The boulders are numerous and large, and cannot have travelled far from the outcrop. On fresh fracture the rock has a "pepper and salt" appearance of dark brown hornblende, greenish-grey augite, and white plagioclase.

In thin section the following minerals were recognised: augite, weakly pleochroic in pale green, as idiomorphic prismatic crystals 0·5 – 1 mm long; hornblende, strongly pleochroic from light to dark brown, as crystals similar in size to augite, and frequently mantling and replacing that mineral; plagioclase, about An_{35} in composition, clear and unaltered, polysynthetically twinned, forming the groundmass; and accessory biotite, apatite, and opaque material. The estimated mode is: augite, 40%; hornblende, 25%; plagioclase, 25%; opaque, 7%; biotite, 2%; apatite, 1%. Although the plagioclase is more sodic than normal for a gabbro, the rock is so classed because of its melanocratic character. Its density is 3·02.

I have collected pebbles of similar gabbroic rocks from the Paringa River, above the junction with the Otoko River.

Tinguaite (Table 1, No. 4)

The occurrence of tinguaites and camptonites in the Haast Valley was described by Turner (1932). Although he did not observe them *in situ*, he deduced from their occurrence in stream gravels that they crop out in the ranges that extend from the headwaters of the Fish River across the

Burke Valley towards the junction of the Haast and Clarke Rivers. During the construction of the Haast-Makarora road, a cutting one mile south of Clarke Bluff exposed a 6-ft sill of tinguaite cutting chlorite 4 subzone schist. This rock was collected and analysed and is described here.

In hand specimen this tinguaite is a dense grey-green rock with a flinty fracture; sparse, white, lath-shaped phenocrysts up to 5 mm long are visible. Weathered surfaces are pale green, and the white phenocrysts stand out clearly. Under the microscope the rock is seen to consist of a dense mat of tiny (0·01 – 0·05 mm long) needle-like crystals of aegirine in an almost irresolvable, colourless groundmass which consists of nepheline, cancrinite, and soda-potash feldspar. The cancrinite can be distinguished by its moderate birefringence, considerably higher than that of nepheline and feldspar. The phenocrysts are mostly soda-potash feldspar, many showing partial replacement by cancrinite; occasional phenocrysts are of sodalite. Calculation from the analysis indicates the following modal composition: soda-potash feldspar, 50%; cancrinite, 15%; nepheline, 15%; aegirine, 15%; sodalite, 5%. The density of the rock is 2·59.

Camptonite (Table 1, No. 5)

This rock was collected as a boulder in Macpherson Creek, which crosses the Haast-Makarora road near the 20-mile peg from Haast. This boulder was particularly interesting as it provided a complete section of a small camptonite dike with a selvage of country rock (biotite schist) firmly welded to each side. The dike is 8 cm thick; it shows a dense chilled margin, 1 cm thick, on each contact with the schist, and a somewhat coarser middle section. The middle section shows small (1 mm) white phenocrysts, which are pseudomorphs of talc and serpentine after olivine. The colour of the rock is dark grey, almost black. The rock is similar to other camptonites described from this region by Turner (1932).

In spite of the dense, fresh appearance of the rock in hand specimen, a thin section shows that the original minerals have been greatly altered, almost certainly by deuteric action rather than by weathering. The rock consists of abundant phenocrysts of olivine, averaging 1 mm long, completely replaced by serpentine and talc, and less numerous phenocrysts of colourless augite, which are fresh and unaltered; the groundmass is a fine-grained aggregate of plagioclase, yellow-brown hornblende, calcite, and opaque material. The density of the rock is 2·99.

DISCUSSION

The significance of the biotite hornfels and the greywacke has been discussed under their individual descriptions. The significance of the igneous rocks has been carefully considered by Turner (1932), and later by Hutton (1943).

The distribution of the igneous rocks shows a suggestive relationship to the regional structure of the schists. They are found along a comparatively narrow zone which begins at the Paringa River (I have not seen any igneous rocks in the schist region north of this river) and extends to the south-west through the middle reach of the Haast River (between the Haast-Clarke junction and Gap Creek), the ranges west of the Makarora River (where these igneous rocks were first observed by Haast (1879, p. 264)), and Lake Wanaka, as far as the Matukituki River and the headwaters of the Shotover River. This zone has a maximum width of about eight miles and a length of almost 100 miles. It is the eastern limb of an anticlinal structure in the schist, called the Otago Anticline on the map accompanying the report by Grindley (1958). The axis of this anticline extends from the junction of the Otoko and Paringa Rivers, along the reach of the Haast River between the Roaring Billy and Gap Creek, and from there in an almost straight line to the Matukituki River at Mt Niger. It seems plausible to ascribe the intrusion of the igneous bodies to the same forces that produced this anticlinal structure.

Turner (1932) discussed the evidence for the age of intrusion and came to the conclusion that these igneous rocks were probably injected in Early Tertiary times. Later Hutton (1943) decided that the date of intrusion is at least as recent as Whaingaroan (Early Oligocene). I would concur with the latter opinion.

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POTASSIUM-ARGON AGES OF METAMORPHIC ROCKS AND GRANITES FROM WESTLAND, NEW ZEALAND

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(Received for publication, 19 January 1961)

Abstract

Samples of schist and gneiss from the Southern Alps in Westland have given potassium-argon ages of less than 10 million years, except for one specimen, which gave an age of 76 million years. As the time of metamorphism, on geological evidence, was early Cretaceous or older, these low values for age are interpreted as reflecting argon loss during deep burial prior to late Tertiary uplift along the Alpine Fault. Biotite from a pegmatite within the schists and gneisses gave an age of 25 million years. Argillite from the practically unmetamorphosed rocks east of the Main Divide gave an age of 166 million years. Granite from Rotomanu gave an age of 70 million years; granite from the Paringa River, an age of 286 million years. Since the latter granite is intruded into rocks of the Greenland Series, this series must be pre-Permian.

Introduction

During field work in the Southern Alps in 1954 several specimens of biotite schist and biotite gneiss were collected. From one of these, a gneiss from Cone Rock, at the terminal of the Fox Glacier, a quantity of biotite was extracted and was dated by the potassium-argon method by Professor G. Curtis and his co-workers at the University of California. It gave an age of five million years, remarkably low for a metamorphic rock for which the geological evidence indicated the age of metamorphism as lower Cretaceous or older. During further field work in 1958 additional rock specimens were collected from several localities, the biotite (muscovite in specimen 762) extracted, and the potassium-argon ages determined by Professor P. M. Hurley and his co-workers at the Massachusetts Institute of Technology. Their results have recently been published (Hurley *et al.*, 1960), but since the publication is not readily available, these results (refined and supplemented by additional work) are reproduced here (Table 1), together with a discussion of the geological interpretation.

Description of the Specimens

The petrological descriptions of the specimens, and their exact locations, are as follows (the numbers are the original field collection numbers):

762: Haast-Makarora road, at Clarke Bluff (junction of Haast and Clarke Rivers). The rock is a coarsely foliated quartz-albite-clinozoisite-chlorite-muscovite schist (chlorite 4 subzone); it contains accessory amounts of pyrrhotite and apatite.

781: Haast-Makarora road, at Halfway Bluff, 13·1 miles from Haast Airfield. The rock is quartz-oligoclase-muscovite-biotite gneiss, with accessory tourmaline, apatite, clinozoisite, and opaque material.

205: South bank of Wanganui River, just below Hende Creek, Mount Bonar Survey District. The rock is a quartz-oligoclase-muscovite-biotite schist, with accessory almandine, clinozoisite, tourmaline, and opaque material.

680: Wilson Rock, Waiho Valley, near terminal of Franz Josef Glacier. The rock is a quartz-oligoclase-muscovite-biotite-almandine schist, with accessory opaque material.

313: East bank of Hokitika River, 4·4 miles at 202° from Trig CW, Toaroha Survey District. The rock is a quartz-oligoclase-muscovite-biotite schist, with accessory almandine, clinozoisite, tourmaline, and opaque material.

681: Cutting 0·4 miles south of Rotomanu railway station. The rock is a granite consisting of quartz, microcline, plagioclase, biotite (with a little replacement by chlorite), and muscovite, with accessory apatite; it was mapped as Tuhua granite by Morgan (1911).

669: One mile north of Paringa River, a few yards west of Main South Road. The rock is a granite consisting of quartz, microcline, plagioclase, biotite, and hornblende, with accessory sphene, apatite, and zircon; some biotite flakes are partly replaced by chlorite.

864: Mica mine (worked 1944–45), Moeraki River. The sample used for analysis was cut from a large plate of biotite from a quartz-feldspar-muscovite-biotite pegmatite; the country rock is a quartz-oligoclase-muscovite-biotite schist.

133: West bank of Hopkins River, at junction with Dobson River (north-west Otago). The rock is an argillite, consisting of quartz, albite, muscovite (sericite), chlorite, and clinozoisite, with accessory stilpnomelane. As it was not possible to separate the sericite mechanically, the potassium and argon determinations were made on the whole rock.

TABLE 1—Potassium-Argon Ages of Rocks from Westland, New Zealand (Hurley *et al.*, 1960)

M.I.T. Number	Mason Number	Rock and Locality	K%	A^{40}/K^{40}	K-A Age (m.y.)
M-3957	762	schist Clarke & Haast R.	8·01	·0046	76
B-3956	781	gneiss Haast R.	7·19	·00052 ± ·00008	8 ± 2
B-3952	205	schist Wanganui R.	6·57	·0004 ± ·0002	7 ± 3
B-3953	680	schist Franz Josef Glacier	6·50*	·0002 ± ·0001	4 ± 2
B-3951	313	schist Hokitika R.	6·63	·0002 ± ·0001	4 ± 2
B-3950	681	granite Rotomanu	7·25	·0041	70
B-3954	669	granite Paringa R.	6·12	·0181	286
B-3955	864	pegmatite Moeraki R.	7·81	·00153 ± ·00006	25 ± 1
R-3958	133	argillite Hopkins R.	3·72	·0102	166

*By typographical error this appeared as 1·50 in the original publication.

DISCUSSION

The age of the metamorphism that formed the schists of the Southern Alps has been the subject of diverse opinions on the part of New Zealand geologists. In the last century the schists were often considered to be Archaean, or at least pre-Devonian, since unmetamorphosed Devonian rocks occur in the north-western part of the Alps in the Nelson district. (These rocks are, however, west of the Alpine Fault, and were not involved in the orogeny which metamorphosed the schists.) More recently, opinion has crystallized around two viewpoints: (1) the schists are Paleozoic sedimentary rocks metamorphosed in a pre-Triassic orogeny; (2) the schists are Triassic (and possibly older) sedimentary rocks metamorphosed in an early Cretaceous orogeny. The crux of the argument between these two viewpoints is whether the fossiliferous Triassic rocks in the Southern Alps grade into the schists or are separated from them by an unconformity (an unconformity which, however, has not been recognised in the field). The second viewpoint received some support from the analysis of uranothorite from Gillespie's Beach, South Westland (Hutton, 1950); although the uranothorite was detrital its provenance was almost certainly from the schist belt. The Pb: U + Th age was 119×10^6 years, equivalent to early Cretaceous. The field evidence collected during the present investigation favours the second viewpoint.

At first glance, therefore, the ages of less than 10 million years for the schists and gneisses in Table 1 (except specimen 762) are rather startling. It seems unreasonable on geological grounds to postulate a post-Cretaceous metamorphism for these rocks. Low-grade schist pebbles are common in Cretaceous conglomerates in Otago, as for example in the Naseby district (Harrington, 1955). However, high-grade (biotite) schist pebbles are unknown in Tertiary conglomerates, and appear first in Pleistocene moraines in Westland. It seems therefore that the high-grade schists and gneisses were first exposed to erosion in Pliocene or Pleistocene times, by comparatively rapid uplift along the line of the Alpine Fault. The present relief on the fault is 12,000 ft in the central part of the Alps, and the total uplift has certainly been much greater, to provide the immense amount of fluvio-glacial debris on the Westland coastal strip. It is therefore conceivable that the biotite-bearing schists have been at considerable depths during most of the Tertiary period, and hence at a temperature at which argon would diffuse out of the mineral as it was formed. Hurley and his co-workers believe that temperatures of 300°C or greater are required for the loss of argon in this way. Assuming a geothermal gradient of 30°C/km, a temperature of 300°C would correspond to a depth of 30,000 ft; a geothermal gradient of 20° C/km, a depth of 45,000 ft. This suggests an uplift of between 30,000 and 45,000 ft on the Alpine Fault since the beginning of the Pliocene.

The potassium-argon ages of the schists and gneisses record the time since the radiogenic argon was retained within the crystal structure of the biotite. This is evidently much later than the time at which the biotite crystallized, i.e., the time of metamorphism of these rocks. The only clue to the time of the metamorphism is provided by the 76-million-year age of the chlorite-muscovite schist (specimen 762). This rock is of much lower grade of metamorphism than the biotite-bearing schists and gneisses, so that its original temperature of metamorphism was lower, and it lies farthest from the Alpine Fault. It is quite improbable, however, that the potassium-argon age for this rock is the actual age of the metamorphism; some argon loss since crystallization of the muscovite has probably occurred. The figure of 76 million years does indicate that the metamorphism is pre-Tertiary; the geological evidence suggests that the metamorphism was probably early Cretaceous.

The significance of the 25-million-year age of the biotite from the Moeraki River pegmatite depends upon the interpretation of the geological environment of the pegmatite. Wellman (1955, p. 16) wrote: "The origin of these pegmatites is somewhat uncertain. They do not transgress the schistosity planes, show no contact effects, and appear to grade laterally into the enclosing schist. They seem to have formed by recrystallization of particular bands in the schist rather than by intrusion." My own observations agree with those of Wellman, and I would interpret these pegmatites as formed by the segregation of a low-melting fraction of the country rock during the regional metamorphism. This would make the probable age of the pegmatites early Cretaceous. The 25-million-year age would then be due to argon loss as a consequence of deep burial during most of the Tertiary era. The somewhat higher age for the pegmatite biotite in comparison to the biotite from the schists may perhaps be ascribed to the greater retentivity for argon of the large biotite crystals in the pegmatite.

The potassium-argon age of the argillite poses a number of problems. The rock belongs to the greywacke-argillite formation which makes up the Southern Alps east of the Main Divide, and which grades into the metamorphic rocks to the west. In the field the argillite and the interbedded greywacke are indurated but apparently unmetamorphosed; thin sections, however, show accessory stilpnomelane, evidently produced by mild metamorphic recrystallization. These rocks are mapped as belonging to the chlorite 2 subzone, but are close to the chlorite 1 – chlorite 2 boundary. The simplest interpretation would be to consider the potassium in the argillite to have been incorporated in the sericite during diagenesis, and the potassium-argon age to give the elapsed time since diagenesis. The age of 166 million years, on the current time-scale, would be near the Triassic-Jurassic boundary, which is not inconsistent with the sparse fossil evidence. The presence of accessory stilpnomelane suggests that these rocks were affected by the later regional metamorphism, which would tend to cause some argon loss and hence lower the potassium-argon age. No detrital potassium feldspar was detected in the argillite, so that the possibility of "inherited" argon in the rock is unlikely.

The ages of the two granites must be considered independently of those of the schists and gneisses, since the granites are west of the Alpine Fault. As far as the granite at Rotomanu is concerned, Morgan (1911, p. 77) has admirably summed up the geological evidence for its age.

> "Since the Tuhua granites intrude rocks of the Greenland Series in all parts of North Westland, it is evident that they are Post-Greenland in age. Many pebbles of granite occur in the coal-measure conglomerate near the mouth of the Ten-mile Creek, and therefore it may be supposed that the Tuhua rocks are not only pre-Tertiary, but date back to at least the middle of the Mesozoic period, for a long time must have been required to expose the parent granite by the process of denudation. It may, however, be pointed out that the granite from which the pebbles in question were derived probably occurred to the west of the present coast-line, and may not have been of the same age as the Hohonu and Te Kinga bosses. Indeed, it is not quite certain that even the Tuhua granites are all of approximately the same age, as will, however, be assumed in this bulletin, and therefore, in the absence of definite age-evidence, they cannot certainly be correlated with those of Nelson or other parts of New Zealand."

The granite at Rotomanu is part of the Te Kinga boss. The geological evidence is not inconsistent with the potassium-argon age of 70 million years (i.e., late Cretaceous). Of course, the same caveat holds that this age is a minimum one, if the granite remained above about 300°C for a long time after intrusion and crystallization. However, the granite is intrusive into greywacke of a very low grade of metamorphism, indicating that the country rock was at a comparatively low temperature when the granite was intruded and has not been metamorphosed since. Under these circumstances the age of 70 million years may well be close to the actual time of intrusion of the granite at Rotomanu.

The same considerations apply to the granite at Paringa. This region has been mapped by Wellman (1955), who shows the granite as pre-Cretaceous, intrusive into greywackes of pre-Cambrian or early Paleozoic age; these greywackes are correlated with the Greenland Series of North Westland on lithological and structural similarities. The age of 286 million years (late Carboniferous) is consistent with the geological evidence. The great age of the granite at Paringa relative to the Alpine schists is of particular interest as indicating that at least this section of Westland, west of the Alpine Fault, has been a relatively stable foreland throughout Mesozoic and Tertiary times.

ACKNOWLEDGMENTS

I would like to express my thanks and appreciation to Professor G. Curtis for the original determination of a potassium-argon age of a Westland schist, and to Professor P. M. Hurley and his co-workers, for the series of determinations which form the subject of this paper.

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NOTE ON KAWITI BASALT AND HYDROLOGY OF KAWAKAWA AREA, NORTHLAND

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Abstract

Maps showing the locality, distribution, and surface contours of a basalt flow from Kawiti scoria cone are presented. The Kawiti Basalt is no older than late Quaternary and is probably Holocene. Water supplies for each formation in the Kawakawa area are discussed, and pollution dangers, particularly in the Moerewa Valley, are noted. Probable well yields are: Taheke Basalts (including Kawiti Basalt Member), up to 6,000 g.p.h.; Te Kuiti Group 500+ g.p.h.; Recent alluvial deposits, 0–250 g.p.h.; Waipapa Group, 50–200 g.p.h.; high-level gravels, up to 50 g.p.h.; Horeke Basalts, up to 50 g.p.h.; Onerahi Formation, Pokapu Limestone, and Mangakahia Group, yield little or no water.

INTRODUCTION

Water-supply potential of the Moerewa Valley was surveyed recently, together with that of the area covered by sheet N.Z.M.S. 86, N15/6. This work presented an excellent opportunity to investigate the Kawiti Basalt, and this paper includes both definition and description of the Kawiti Basalt, and a description of the hydrology of sheet N15/6.

The locality of the Kawakawa area is shown in Fig. 1. Detailed geology and drillhole locations are given in Fig. 2, which is extended westwards beyond N15/6 to include Kawiti Cone. Table 1 presents stratigraphic and

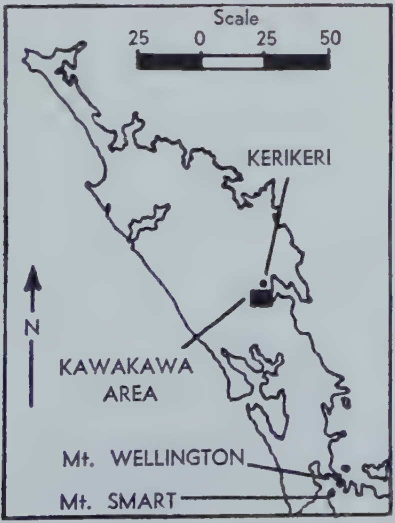

FIG. 1—Locality may of Kawakawa area.

water-supply data for each drillhole and gives the thickness of each formation penetrated. The lithologies and water potentials of these formations are summarised in Table 2 and described in detail in the latter half of the paper.

Because of the rapid expansion of industry and residential areas, particularly in the Moerewa Valley, a note on pollution dangers is included. The probability of contamination of water from the various aquifers is summarised in Table 2. Water analyses from wells at the Bay of Islands County Depot and the Bay of Islands Dairy Factory are given in Table 3.

KAWITI BASALT MEMBER

Status

The Kawiti Basalt is here defined as a member of the Taheke Basalts (Kear and Hay, 1961; after Mason, 1953).

Name

Kawiti (400 ft), illustrated in Fig. 3, from which the Member is named, is a basaltic scoria cone rising 200 ft above the valley floor at the western extremity of the Moerewa Valley, Kawakawa Survey District. Ferrar (1925, p. 19) briefly referred to "the recent scoria cone of Kawiti", but later (p. 55) discarded "Kawiti" and used the name "Tui Pa scoria cone", presumably after a Maori fortification on the summit; later still (p. 71) he referred to "the scoria beds forming Tui Pa Hill". In this paper Ferrar's original name will be retained for the cone and the basalt derived from it.

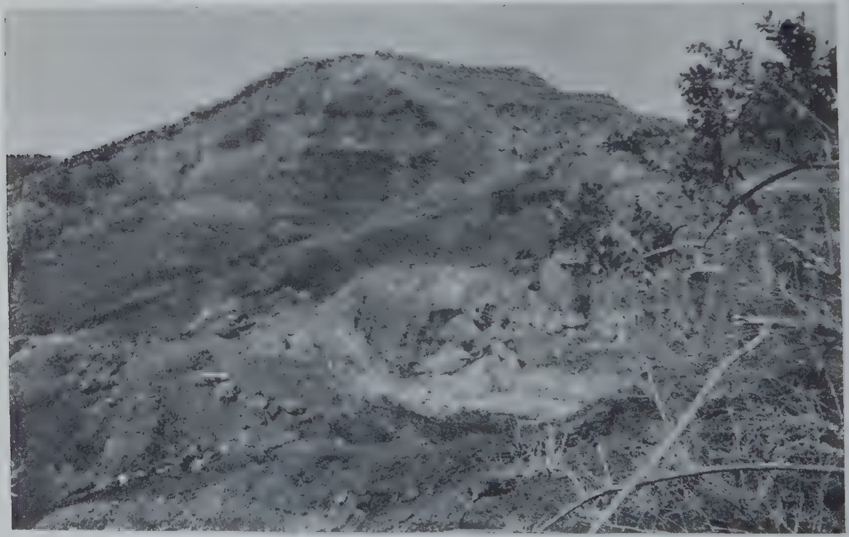

FIG. 3—Kawiti cone from the north, showing quarry face and old Maori fortification on the summit.

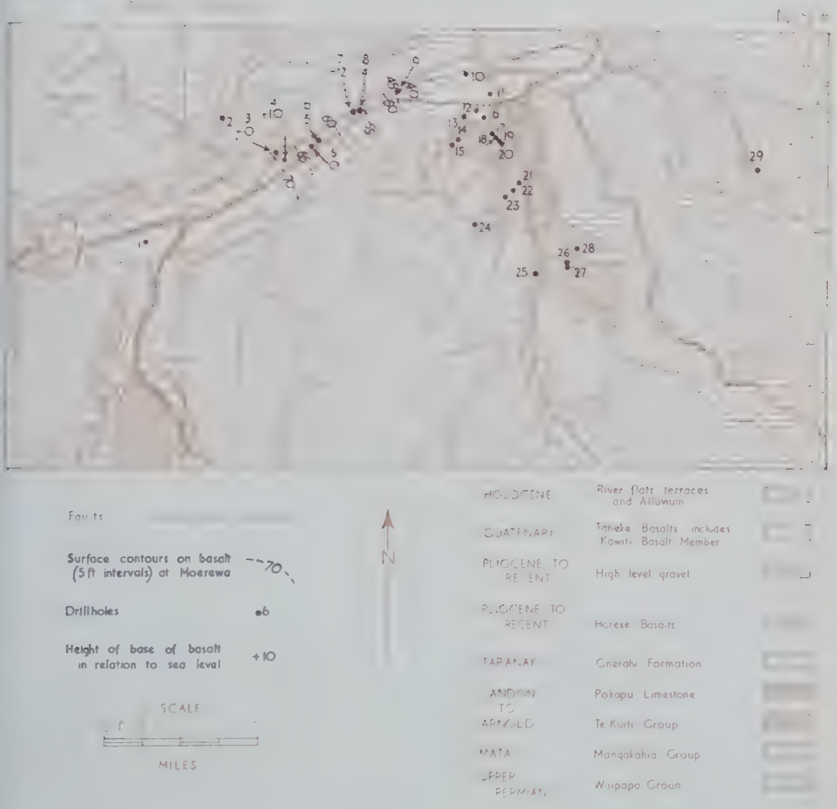

FIG. 2—Detailed geological map showing distribution of basalt, surface contours on basalt at Moerewa, and drillholes within N15/6 and part N15/5.

Distribution

Kawiti cone is located at the intersection of the Kawakawa Fault with a north-west-trending fault. The lava flow, half a mile wide and an average of 80 ft thick, extends eastwards for about 5 miles. It is confined to the Moerewa Valley fault-angle depression by an up-faulted Waipapa Group greywacke block to the north and by Cretaceous to Miocene claystones to the south and has displaced the course of the Otiria and Waiharakeke streams (Ngapipito and Ramarama of Ferrar, 1925) against the north and south sides of the valley respectively (Fig. 4).

The distribution of the basalt, and surface contours at 5 ft intervals at Moerewa, are shown in Fig. 2. A surface slope of 1°, to within half a mile west of Otiria, flattens out to 1/5° at Moerewa and continues to its terminal a mile west of Kawakawa, where the basalt is estimated to be 50 ft thick (Fig. 5). The quantity of scoria and basalt is estimated at 0·05 cubic miles.

Description

Beds of red scoria from pea size to blocks up to 2 ft constitute the bulk of Kawiti cone. At the railway ballast pit the basalt is blue-grey, slightly to highly vesicular, with its vesicles unfilled. Crystals of feldspar and weathered olivine up to 2 mm long are fairly common, with less common olivine nodules up to 10 mm. Near Moerewa, 4 miles from the source, basalt in the bank of the Waiharakeke Stream is more dense and less vesicular than at the ballast pit.

A petrographic description of a fine-grained, pinky-grey scoriaceous basalt with conspicuous phenocrysts of feldspar and olivine from Kawiti (grid ref. N15/475350) is given by Miss G. A. Challis, N.Z. Geological Survey, as follows:

> Under the microscope, the rock is holocrystalline and porphyritic. Phenocrysts of plagioclase (An_{65-67}) and olivine up to 2 mm in length, together with rare phenocrysts of augite, occur in a fine-grained groundmass of feldspar laths, granular olivine, augite, and iron ore. Flow texture is moderately well developed in the less scoriaceous phase of the basalt, and well developed in the highly scoriaceous phase.
>
> The feldspar is sometimes zoned and occurs in sharp, water-clear crystals. Other phenocrysts are badly corroded, and the corrosion channels are filled with a pale brown glass. The olivine is fairly fresh, but some alteration to iddingsite can be seen. A few crystals of olivine have included plates of dendritic iron ore. Augite is rare as phenocrysts, but fairly common as small grains in the groundmass.
>
> In one slide, alternating bands of fine-grained and cryptocrystalline material can be seen. In the cryptocrystalline bands, the phenocrysts are scarcer and smaller, and there is abundant dusty magnetite in the groundmass. In the hand specimen these bands show as dark streaks.

At Moerewa Freezing Works (7, Fig. 2), Moerewa Dairy Factory (6, Fig. 2) and Bay of Islands County Council yards (4, Fig. 2), drillhole logs show the basalt to be consistently scoriaceous, fractured, and fissured (Table 4). Similar logs are recorded for other drillholes in the Moerewa area (Table 1).

TABLE 1—Abbreviated Logs of Drillholes in the Kawakawa Area. (Thicknesses of formations penetrated in feet.)

Drillhole No.	Locality	Superficial Deposits (inclu ding alluvium)	Taheke Basalts (Kawiti Basalt)	Pre-Kawiti Quaternay Deposits	Horeke Basalts	Onerahi Formation	Te Kuiti Group	Waipapa Group	Total Depth	Yield (in g.p.h.)	Remarks
1	Martinson, Otiria	8	35	–	–	–		–	43	550	Casing 21 ft. Pump 25 ft.
2	Helier, Haupuru Rd	–	–	–	–	45	–	32	77	Nil	Water hard in this locality.
3	McArthy, Moerewa	15	55	–	–	–	–	–	70	500	Casing 15 ft. Hole diam. 2 in.
4	Council Yards, Moerewa	13	49	25	–	–		–	87	4000–6000	Casing 60 ft. Hole diam. 6 in.
5	School, Moerewa	18	46	–	–	–	–	–	64	750	Casing 18 ft. Static W.L. 27 ft.
6	Dairy Factory, Moerewa	12	44	1	–	–	–		57	5000	Pump 54 ft. Static W.L. 26 ft.
7	Auckland Farmers Freezing Co. Moerewa	8	54	18	–	–	–	–	80	2500	Hole diam. 5 in.
8	Auckland Farmers Freezing Co., Moerewa	12	41	82	–	–	–	–	135	4500	Hole diam. 4 in.
9	Palmer, Moerewa	8	13	–	–	–	–	–	21	500	
10	Swamp near Kawakawa	172	–	–		–	–	2	174	–	Coal prospecting (Hay, 1947, drillhole No. 4)
11	Kawakawa	90	–	–		–	–	–	90		Coal prospecting (Healy, 1946, drillhole No. 13)
12	Kawakawa	–	–	–	–	–	290	–	290	–	Coal prospecting (Healy, 1946, drillhole No.12)
13	Kawakawa	81	–	–	–		20	–	101	–	Coal prospecting (Hay, 1947, drillhole No. 1)
14	Kawakawa	66	–			–	483	47	596		Coal prospecting (Healy, 1946, drillhole No. 6)
15	Kawakawa	11	–	–	–		674	4	689		Coal prospecting (Healy, 1946, drillhole No. 7)
16	Kawakawa	51	–	–	–	–	387	–	438	–	Coal prospecting (Healy, 1946, drillhole No. 5)

17	Near School, Kawakawa		–				282		282		Coal prospecting (Healy, 1946, drillhole No. 2)
18	Near School, Kawakawa	–	–	–	–	–	138	–	138	–	Coal prospecting (Healy, 1946, drillhole No. 4)
19	Near School, Kawakawa		–				175	–	175		Coal prospecting (Healy, 1946, drillhole No. 1)
20	Near School, Kawakawa		–			–	173	–	173		Coal prospecting (Healy, 1946, drillhole No. 3)
21	About 1 mile S. of Hospital	83	–	–	–	–	85	16	184	–	Coal prospecting (Healy, 1946, drillhole No. 9)
22	About 1 mile S. of Hospital	–	–	–	–	–	260	–	260	–	Coal prospecting (Healy, 1946, drillhole No. 10)
23	About 1 mile S. of Hospital	46	–			–	176	1	223	–	Coal prospecting (Healy, 1946, drillhole No. 8)
24	About 1 mile S. of Hospital	–	–	–	–	–	380	–	380	–	Coal prospecting (Healy, 1946, drillhole No. 11)
25	Reihana, Waiomio	–	–	–	–	–	–	–	600	500+	Artesian soda water.
26	Caves Rd, Waiomio	24	–	–	–	–	7	–	31	–	Coal prospecting (Hay, 1947, drillhole No. 3)
27	Caves Rd, Waiomio	24	–			–	239	19	282		Coal prospecting (Hay, 1947, drillhole No. 3A)
28	Caves Rd, Waiomio	26	–				114	17	157	–	Coal prospecting (Hay, 1947, drillhole No. 2)
29	Pakarau Rd	11	–	–	19	–	–	70	100	75	Water from contact between basalt and Waipapa Series.

Age and Correlation

At the ballast pit, pieces of wood, a sample of which is awaiting radiocarbon dating, and carbonaceous material are contained within the underlying clay (resting on claystones) near the basalt contact, and scoria beds may be seen overlying claystones, mapped as Onerahi Formation by Ferrar (1925), in railway cuttings at the base of the cone.

Bell and Clarke (1909) named the older basalts forming Kerikeri tableland the Kerikeri Series and considered them of Miocene or post-Miocene age. They recognised, but did not name, younger basalts which they considered of post-Miocene age.

The Kerikeri tableland basalts rest on plant beds which, according to McQueen (*in* Laing, 1954), are younger than Castlecliffian. Though only slightly dissected these basalts are deeply weathered, and Laing (1954) considered them older than Recent and tentatively assigned them to the Upper Pleistocene.

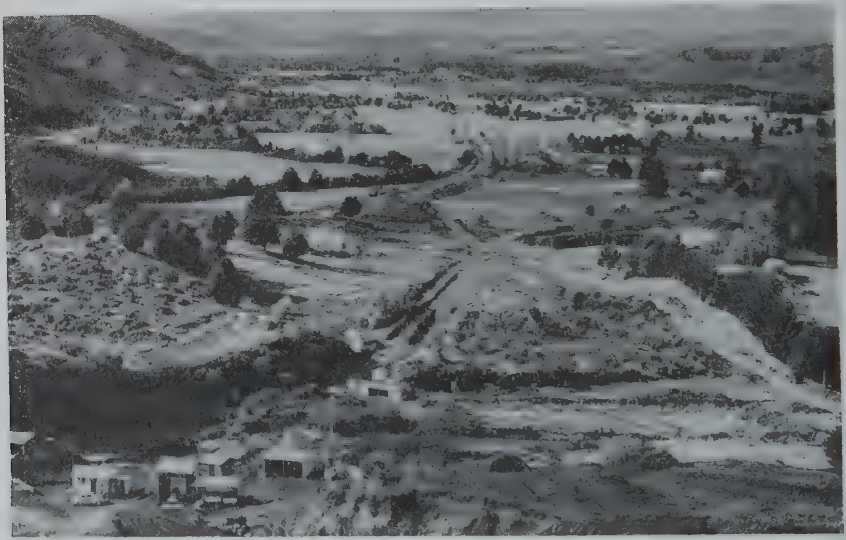

FIG. 4—View from summit of Kawiti looking in direction of basalt flow (i.e., north-east). Up-faulted Waipapa Series greywacke block top left, and basalt flow filling valley in the fault-angle depression.

Ferrar (1925) mapped the Moerewa Valley basalts (Kawiti Basalt) as younger than the Kerikeri tableland basalts; if the age assigned by Laing to the latter is correct, the Kawiti Basalt is Hawera or younger.

Kear (1957) defined four stages in the erosion of volcanic cones; he considered cones that are essentially similar to those of active volcanoes to be in the Volcano Stage, and in general of Holocene or late Hawera age. Kawiti Cone is but little eroded and by Kear's criteria would be late Hawera or younger.

Fergusson and Rafter (1955, N.Z. ^{14}C No. 11) dated a basalt flow from Mount Wellington, Auckland (E. J. Searle, pers. comm.), as 9,150 years ± 80 years B.P., and later (1959, N.Z. ^{14}C No. 225) dated the Mount Smart flow, Auckland, as 9,000 ± 160 years B.P. (Fig. 1). The surface form of these flows is rugged, with abundant basalt blocks, and resembles that of the Kawiti flow. Further, basalts from Kawiti quarry and Mount Smart quarry show little difference in degree of weathering at quarry faces. It is likely therefore that Kawiti also erupted during the Holocene.

In all drillholes the base of the basalt was penetrated at about present sea level, and the shells and mud recorded from about this horizon in the drillhole (2, Table 4) at the Dairy Factory at Moerewa, and about 35 ft below sea level in the hole (4, Table 4) north of Kawakawa, suggest that the sea at the time of eruption was at about the same level as at present (Fig. 5).

The log of the drillhole at Kawakawa (10, Table 4, Fig. 5) records alluvial sand, clay, gravel, and timber, overlain by a 2 ft thick bed of grey sand with shells, at a depth of 60–62 ft, i.e., about 35 ft below sea level; a similar shell bed 5 ft above sea level immediately underlies the basalt at the Dairy Factory, Moewera (6, Fig. 5). As the sediments recorded in the Kawakawa drillhole appear to be terrestrial rather than marine, it seems probable that these two shell beds were deposited during a marine transgression that preceded the Kawiti Basalt. If extruded during a time of high sea level within the Holocene, it would be no more than 5,000 years old.

Evidence of the age of the Kawiti Basalt is thus inconclusive, but it is no older than late Quaternary and probably as young as Holocene.

HYDROLOGY

GROUND WATER POTENTIAL OF INDIVIDUAL FORMATIONS

Recent Alluvial Deposits

The river flats, terraces, and alluvium are composed of clays, sands, silts, peats, gravels, and rare buried timber and shell beds (drillhole 10, 0–172 ft, Table 4). The gravels associated with alluvial deposits are usually the best source of ground water. The quantity available largely depends on their thickness and permeability. Sands are usually good aquifers but their water-bearing potential depends upon the thickness of the bed, grain size, clay content, and cementing material. Clays and silts, being fine-grained and relatively impermeable, would not be expected to yield large supplies of water.

No large supplies could be expected from peat beds; moreover, water from this source usually has a high iron and organic matter content.

Taheke Basalts (Kear and Hay, 1961; after Mason, 1953)

Hay (1952), in discussing the aquifers of Northland, stated that scoriaceous basalt, or basalt fissured by cooling, nearly always occurs at the contact with the underlying sedimentary rocks, and that scoriaceous layers, ash beds, or fissured zones may occur within the basalt sheet. These fissured or scoriaceous rocks would yield good supplies of water.

Abundant supplies are usually obtainable from drillholes in the Kawiti Basalt. All drillholes have penetrated "fissured" or "fractured" rock at different depths, and therefore none is likely to be a failure. The yield would depend upon the depth of the hole, but could normally be expected to be between 2,000 and 5,000 gallons per hour (g.p.h.) from a depth of 50–80 ft.

Basalts forming Ngahuha Hill, in the north-west corner of the area shown in Fig. 2, may yield good supplies of water. In the absence of drillhole information, this assumption is based on their being mapped as "younger basalts" by Ferrar (1925), and they would therefore probably be similar in lithology to the water-bearing Kawiti Basalt.

High-Level Gravels (Ferrar, 1925)

High-level gravels cap the hills immediately south of the Kawakawa-Moerewa Road and are also exposed in a cutting at the Kawakawa Railway Station, where they consist entirely of sub-angular, weathered greywacke pebbles in a matrix of clay. No drillholes are known in them, but because of their small areal extent and thinness they are not likely to yield large supplies of water.

Horeke Basalts (Mason, 1953)

Olivine basalt sheets and scattered boulders (Ferrar, 1925) are preserved solely as remnants capping the hills to the east and south of Kawakawa. The basalt is fine-grained in the boulders, and deeply weathered to an orange-brown clay on the ground surface.

Some springs emerge from the basalt – Waipapa Group contact and provide sufficient water for domestic and small farm use. A drillhole in Pakarau Road (Fig. 2, drillhole No. 29) penetrated 30 ft of basalt including the weathered surface zone and 70 ft of weathered clays grading to unweathered solid blue rock; it yielded 75 g.p.h., presumably from the basalt–Waipapa contact, or from fractures and fissures in the basalt or underlying rocks.

Yields from the Horeke Basalts would probably be small, but the water fairly pure.

Onerahi Formation (Kear, 1959; after Ferrar, 1925), *Pokapu Limestone* (Hay, 1960), *and Mangakahia Group* (Hay, 1960)

About half of the area is underlain by impermeable claystones and impure limestones of the Onerahi Formation, argillaceous limestone and argillaceous limestone with glauconitic sandstone bands belonging to the Pokapu Limestone, and fine-grained mica sandstones, calcareous shales, mudstones, and siliceous claystones of the Mangakahia Group. Rocks belonging to each of these three groups would yield little or no water. Drilling in them is therefore successful only if the rocks underlying are water-bearing and are at reasonably shallow depths (e.g., near the eastern boundary with the underlying Te Kuiti Group).

TABLE 2—Water-bearing Properties of Rocks

Formation	Lithology	Water Potential	Remarks
Recent alluvial deposits	Sand, silt, gravel, peat.	Fair to good. Usually good water but may be iron-bearing if drawn from peat. 0–250 g.p.h.	Water obtainable provided gravel beds are unweathered and permeable.
Taheke Basalts (includes Kawiti Basalt Member)	Scoriaceous basalt flows.	Good. May be subject to pollution. Yields up to 6,000 g.p.h.	Usually high yields obtained from younger basalts.
High level gravels	Angular and sub-angular pebbles in a matrix of clay.	Poor. Probably fair quality. Yields up to 50 g.p.h.	Thin veneer on older rocks. Probably too thin and too impermeable to be good aquifer.
Horeke Basalts	Weathered volcanic flows, with numerous dense basalt boulders scattered on ground surface.	Poor. Probably fair quality. Yields up to 50 g.p.h.	Basalt usually too weathered or dense to yield water. Sometimes small supplies from contact of basalt and underlying rock.
Onerahi Formation	Claystones and impure limestones.	Nil, usually surface dams.	Impermeable claystones.
Pokapu Limestone	Argillaceous limestones and argillaceous limestones with greensand bands.	Nil.	Impermeable argillaceous limestones.
Te Kuiti Group	Sandstones, crystalline limestones, conglomerates, and coal-measures.	Fair to good. May be soda water. Yields 500+ g.p.h. from limestones.	Solution holes containing water could be expected in the limestones. Sandstones, conglomerates, etc., may or may not yield water.
Mangakahia Group	Siliceous claystones, claystones, and impure limestones.	Nil, usually surface dams.	Impermeable claystones.
Waipapa Group	Indurated siltstones and sandstones.	Poor to fair. Probably good quality when Waipapa rocks penetrated below younger rocks, otherwise may be polluted. Yields 50–200 g.p.h.	Too impermeable to yield water except from fissured or fractured zone that may exist near the surface.

Construction of artificial ponds in the impermeable Onerahi, Pokapu, and Mangahikahia rocks, and the surface clays derived from them, is relatively simple. Such ponds are often the only source of water for farms situated wholly within areas of these rocks.

Te Kuiti Group (Kear and Schofield, 1959)

In the Waiomio area, Te Kuiti rocks (Kear, 1959) form hard cyrstalline limestone bluffs, and sandstones, greensands, and coal measure conglomerates are exposed in road cuttings.

Crystalline limestones usually contain solution holes and cavities that would yield plentiful supplies of water if penetrated by a drillhole. The yields of water from drillholes in the sandstones, greensands, and coal-measure conglomerates are unknown. However, Kear (1959) found that the Whangarei Limestone and Ruatangata Sandstone in the Kamo Mine area contain abundant solution cavities containing water.

Drillholes in the Te Kuiti Group may yield "soda" water, as in drillhole 25 at Waiomio (Fig. 2), and at Kamo where bicarbonate mineral water from these rocks is heavily charged with carbon dioxide (Kear, 1959).

Waipapa Group (Bell and Clarke, 1909)

The indurated sandstones and siltstones of the Waipapa Group are in some places fractured and fissured near the surface, but at greater depths they are impermeable.

They would probably yield 50 to 200 g.p.h. from a drillhole in the weathered surface zone, which may be 50 ft thick. Drillholes should not exceed about 100 ft in depth, since there is little point in drilling in the impermeable rock below.

STREAMS

Waiharakeke Stream (average flow 3·69 cusecs) and Otira Stream (average flow 1·38 cusecs) both drain areas of soft claystones and argillaceous limestones. They are sluggish and pass through swampy flats where contamination may occur, and are probably also subject to pollution when they pass through the industrial area.

Tirohanga Stream (average flow 10·6 cusecs) on the other hand flows swiftly over hard Waipapa Group greywackes in its bush-clad upper reaches, and alluvium consisting mainly of hard pebbles for the final two miles of its course. As a result the quality of water from this source would probably be fairly good.

POLLUTION DANGERS

A major consideration in using underground water for domestic purposes is the possibility of pollution. Sewage disposal in the expanding industrial area in the Moerewa Valley is by septic tanks or directly into

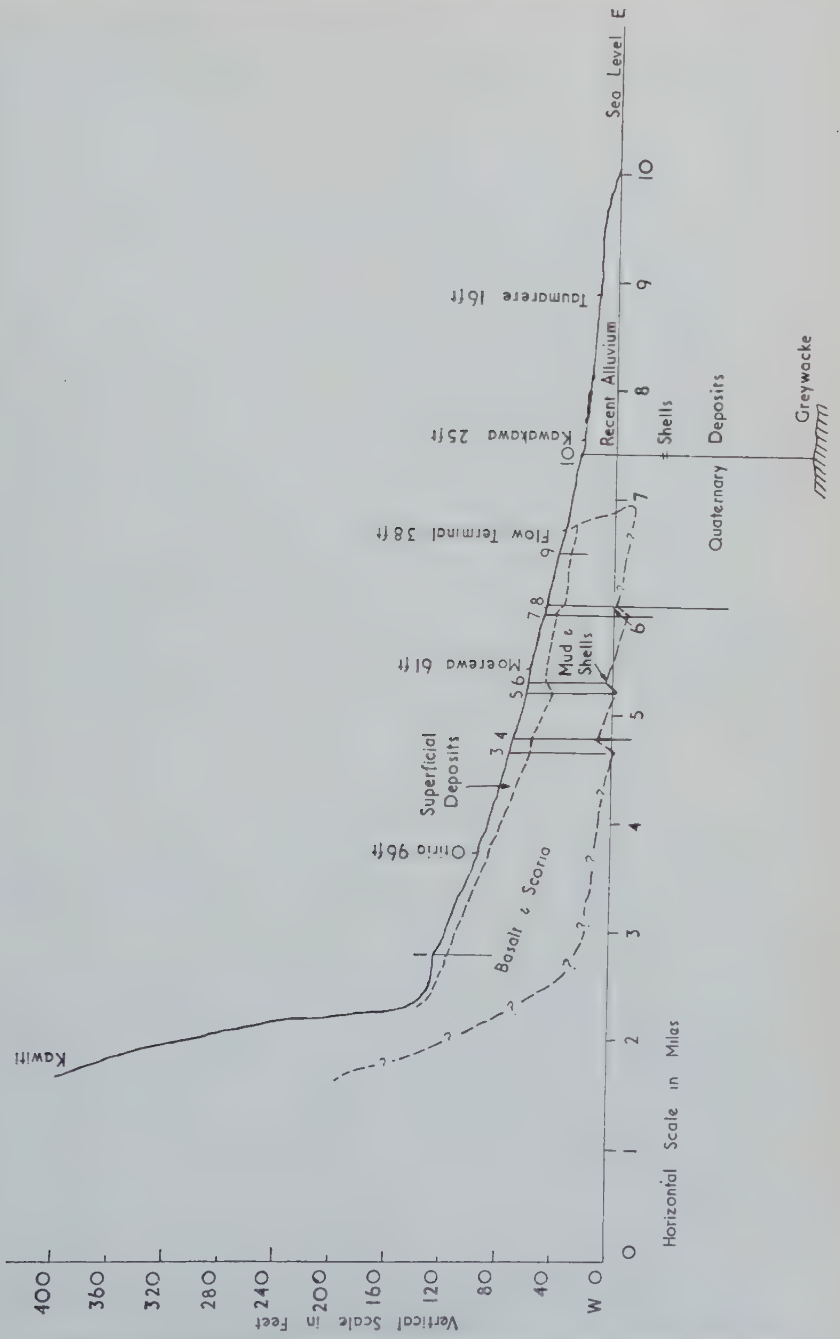

FIG. 5—Longitudinal cross section of Moerewa Valley, showing thicknesses of basalt.

the ground; and in some places industrial waste is pumped into settling ponds. The land not set aside for town expansion is farmed, and part of it is subject to flooding. The Kawiti Basalt is known to be fractured and fissured, and as Caldwell (1938) has pointed out, rocks that are creviced, faulted, fractured, or contain cavities or solution channels, may carry fecal pollution along complicated conduits that are impossible to trace. The United States Public Health Service (1926) stated that the safe vertical depths at which surface bacterial pollution is effectively filtered out are conservatively as follows: "Solid clay, 6 ft; fine sand, 12 ft; gravel, indefinite; fissured rock, no distance—water unsafe without treatment". The same authorities recommended that rural wells in granular material be at least 50 ft from any possible source of pollution, 100 ft from seepage pits and barnyards, and 150 ft from cesspool resources of pollution, but added that these limits and others recommended by State Agencies are largely empirical because of the limited research that has been carried out.

A deep hole is no guarantee that the water would be pure, although as Thomas (1951) states: "The danger of drawing polluted water from wells is far less than in the case of streams". Pollution of wells has usually been traced to faulty well construction.

Clearly it is of the utmost importance that drillholes should be protected from pollution at the ground surface. Beyond this, experience elsewhere is of little value, and nothing can replace analysing water samples, taken from the more important drillholes from time to time, and especially from new ones when brought into production. Pollution is most likely to occur at times of surface flooding, and samples would best be taken at such times.

WATER ANALYSES

Analyses of water from the Council drillhole (4, Fig. 2) between 7 and 23 July 1959 are given in Table 3 (analysed by Govt. Analyst, Auckland). A partial analysis by the Bay of Islands Dairy Company in Moewera, from their own well (6, Fig. 2), is also appended.

The presence of ammoniacal nitrogen in the first four of the five samples from the Council drillhole indicates slight pollution at the time of sampling that may have resulted from matter entering the drillhole while drilling. In all cases the chemical analyses indicate satisfactory water, and the final analysis of 23 July shows the water to be free from pollution.

It is interesting to note than an analysis of the water from the Dairy Factory also disclosed that initially *B. coli* pollution was high. After three months it was nil.

SUMMARY

Adequate supplies of ground water for industrial and domestic uses should be available from the recent alluvial deposits, the Kawiti Basalt, and possibly from the Taheke Basalts and the Te Kuiti Group. Small supplies

(200 g.p.h. and less) may be obtained from high-level gravels, Horeke Basalts, and the weathered surface zone of Waipapa rocks. Virtually no water is normally obtained from Onerahi, Pokapu Limestone, or Mangakahia rocks.

TABLE 3—Water Analyses

(1) Bay of Islands County Depot, Moerewa (Drillhole 4)

	7.7.59	13.7.59	16.7.59	21.7.59	23.7.59
Smell	Faint	Faint	Faint	Faint	Faint
pH	6·0	6·0	6·0	6·0	6·0
	Parts per million				
Chlorine in chlorides	17·0	18·0	17·0	16·0	16·5
Nitrate nitrogen	0·4	Nil	Nil	2·0	2·0
Nitrite nitrogen	Nil	Nil	Nil	Nil	Nil
Ammoniacal nitrogen	0·009	0·008	0·005	0·006	Nil
Albuminoid nitrogen	Nil	Nil	Nil	Nil	Nil
Oxygen absorbed in 4 hrs at 80°F	Nil	Nil	Nil	Nil	Nil
Total solids	122	130	117	109	90
Iron	0·2	0·2	0·2	0·2	0·2
Hardness—Calcium	30	30	22	16	30
Magnesium	10	10	14	20	4
Total	40	40	36	36	34
Total alkalinity	50	40	–	40	30
Agar Plate Count 37°C (per ml.)	10	2	2	2	4
Coliform organisms (MPN/100ml.)	1	1	1	1	5

(2) Dairy Factory, Moerewa (Drillhole 6)

	Parts per million
Hardness	9·4
Calcium	7·5
Carbonate	5·8
B. coli initially	High
after 3 months	Nil

The water would generally be of good quality, but might be polluted in the Kawiti Basalt and Whangarei Limestone, in which there are large underground cavities, or contaminated by peat in the Recent alluvial deposits, or by "soda water" in the Whangarei Limestone.

Water from Waiharakeke Stream and Otiria Stream would probably be slightly contaminated and polluted. Tirohanga Stream would normally be free of both contamination and pollution.

All available drillhole logs are summarised in Table 1. Use of this table in conjunction with Table 2 and Fig. 2 allows estimates of ground water that could be obtained by drilling at any point within the area covered by N.Z.M.S. 86 sheet N15/6.

TABLE 4—Logs of Four Drillholes in the Moerewa Valley

(1) Moerewa Freezing Works (Drillhole 8)

0 – 12 ft	loose rock and soil.
12 – 53 ft	alternating beds of scoria and basalt.
53 – 135 ft	clay, pug, sand, gravel, and boulders.

(2) Moerewa Dairy Factory. (Drillhole 6)

0 – 12 ft	surface clays and scoria
12 – 48 ft	fissured basalt.
48 – 57 ft	boulders.
57 ft	mud and *shells.*

(3) Bay of Islands County Council Yards (Drillhole 4)

0 – 13 ft	broken basalt.
13 – 17 ft	solid basalt.
17 – 21 ft	broken basalt.
21 – 40 ft	very hard basalt.
40 – 53 ft	very broken basalt.
53 – 58 ft	hard basalt.
58 – 61 ft	broken basalt.
61 – 87 ft	silty clay and shingle.

(4) Swamp near Kawakawa (Drillhole 10)

0 – 30 ft	grey fine to sandy clays.
30 – 45 ft	sandy clay with gravel bands.
45 – 60 ft	grey clays.
60 – 62 ft	coarse grey sand with *shells.*
62 – 112 ft	grey and brown clay.
112 – 114 ft	buried timber and sand.
114 – 152 ft	sandy clay with buried timber at bottom, 6 ft.
152 – 172 ft	sand, timber, sandstones.
172 – 174 ft	greywacke.

ACKNOWLEDGMENTS

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SPRINGTIME TEMPERATURE CHANGES IN THE ANTARCTIC STRATOSPHERE

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Abstract

An analysis of temperatures observed in the Antarctic stratosphere during the spring months of 1957 and 1958 showed the occurrence of large and sudden temperature fluctuations, which were quasi-periodic and progressed downwards from the highest observed levels to the low stratosphere. The characteristic features of the 20 km, high-latitude circulation accompanying these temperature fluctuations are shown by selected contour maps for the 50 mb level for the springs of 1957 and 1958. Similarities and differences of stratospheric events between the two springs are noted.

INTRODUCTION

The occurrence in the stratosphere of large and sudden temperature changes during late winter and early spring in northern latitudes has been the subject of much discussion since the "Berlin warming" was noticed in February 1952. On that occasion stratospheric temperatures between the heights of 25 and 30 km increased by 45°C in 48 hours (Scherhag, 1952). In subsequent years several case studies have been made of similar large seasonal temperature changes in the polar and sub-polar stratosphere of the northern hemisphere (Lee and Godson, 1957; Teweles, 1958; Craig and Hering, 1959). The fact that, in some years, the warming at high latitudes occurred in late winter before the return of the sun, favoured the conclusion that these sudden increases in temperature were due mainly to advection of warmer air from other latitudes, and to descending air motions. These processes were associated with the breakdown of the polar cyclonic vortex that dominated the high-latitude stratospheric circulation in winter, and with the disappearance of the "polar night" stratospheric jet stream. This zone of strong westerlies occurs on the boundary of the polar night, where strong horizontal temperature gradients develop as a result of the differential radiational heating inside and outside this boundary during the winter half-year. As the seasonal radiational changes due to the movement of the earth are symmetrical about the Poles, one would expect an even distribution of horizontal temperature gradients around the Poles and circumpolar zonal winds. This, however, is not the case around the North Pole, where marked departures from the zonal flow over preferred areas at high latitudes exist. Amplifications of waves in this zonal flow and the accompanying vertical and horizontal motions were used to explain the anomalous late winter warmings in the stratosphere (Teweles, 1958). The wintertime Antarctic stratospheric vortex was shown to be more intense and more stable than that over the Arctic (Wexler and Rubin, 1956; Wexler, 1959; Palmer, 1959), and it was expected that there would be marked differences between the two polar areas in the nature of the springtime stratospheric circulation changes.

Recently some interesting results on the seasonal latitudinal distribution of ozone for both hemispheres also pointed to significant differences between the two polar regions (MacDowall, 1960). While in the northern hemisphere the maximum ozone amount during the spring occurs near the Pole, in the southern hemisphere this is found near latitude 50° in September and October, the maximum moving near the Pole only later in November and December. In the following an account is given of the temperature anomalies and the accompanying circulation features in the middle stratosphere during the spring seasons of 1957 and 1958.

TEMPERATURE AND WIND REGIMES OF THE ANTARCTIC STRATOSPHERE DURING THE SPRING SEASON

In 1957 and 1958 radiosonde and radar wind observations were made at 17 stations situated on the periphery and interior of the Antarctic Continent (Fig. 1). Of these, only 9 stations yielded reasonably continuous daily records at the 50 mb level (approximately 20 km). Of the few island stations that bridged the vast areas between the Antarctic and mid-latitude

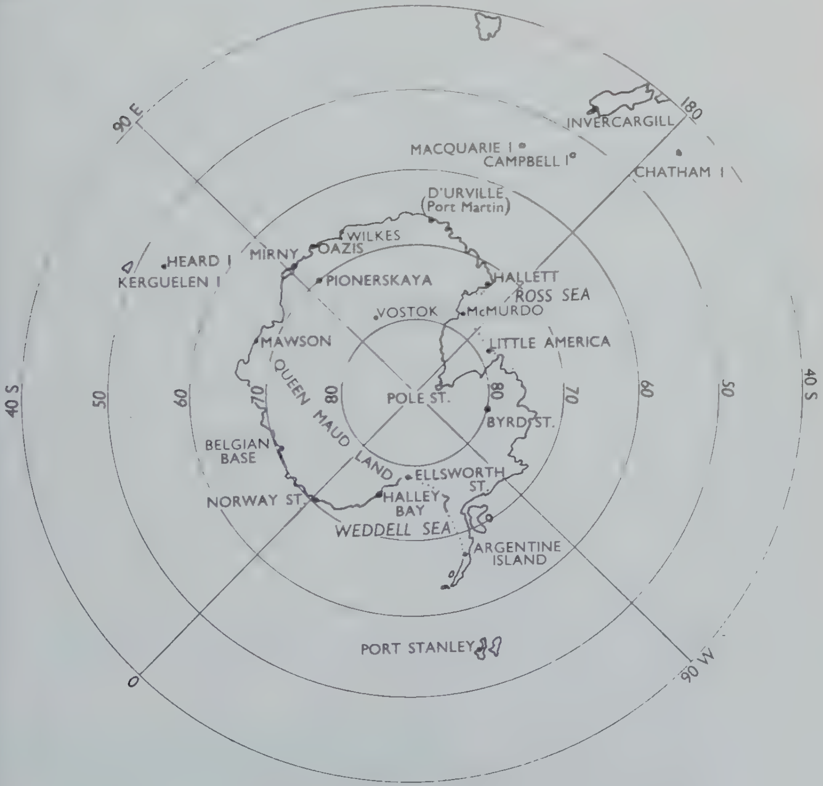

FIG. 1—Location Map of Radiosonde and Radar Wind Stations.

continents, only Macquarie and Campbell Islands had regular radiosonde data. Only a few occasional soundings reached 20 km height at stations in the South American or South African sectors.

The Antarctic stratosphere responds to the disappearance of the sun during the winter by cooling to very low temperatures, in contrast to the troposphere, where the difference between mean summer and winter temperatures is small (Wexler, 1959). It is thought that, while dynamic and meridional transfer processes balance the radiational cooling in the polar troposphere, the polar stratospheric circulation is very stable and meridional exchange processes are very limited, with the stratospheric polar jet stream acting as a barrier between the high and middle latitude circulations. The lowest monthly mean temperature at 50 mb occurs in August and temperatures begin to rise slowly afterwards as the sun returns. The northernmost boundary of the polar darkness at 20 km is 72½° latitude, north of which there is some sunshine at this level every day. One month of darkness exists at 73° latitude, beginning with the second week of June, two months in latitude 75½°, three months in latitude 79°, four months in latitude 84° and five months at the Pole. This latter period starts in April and ends at the beginning of September when continuous sunshine begins there. The latitude of the boundary of the 24 hours sunshine then decreases slowly to reach 70° by the end of October (Court, 1943). The rate of cooling within the boundary of the polar night is rapid at first and slows down after July. It is interesting to note that the difference of the daily totals of incoming radiation between the Pole and the coastal latitudes of Antarctica is a maximum near the end of September, after which it rapidly decreases to zero in the second half of October, and the Pole receives slightly more radiation afterwards until the beginning of the autumn, (Schwerdtfeger, 1960, Fig. 3).

The polar stratospheric circulation at the beginning of the winter is dominated by a circumpolar cyclonic vortex, and owing to the differential heating of the regions inside and outside the polar night boundary, the horizontal temperature gradients and the associated zonal winds become stronger during the polar night. The breakdown of the system might be expected to occur after the return of the sun. The disappearance of the strong horizontal temperature gradients and of the associated jet stream does not occur normally until the middle of November, at about the same time as the amounts of incoming radiation become larger at higher latitudes as mentioned above. The springtime stratospheric warming, however, shows a more complicated structure than would be expected from mainly radiational heating.

Daily temperature soundings from the 200 mb level upwards, (approximately 11 km) are shown on time cross sections from September to November 1957 in Figs. 2–6 for five selected Antarctic stations.

The following points were noted:

(1) Short-period quasi-periodic temperature fluctuations were superimposed on the springtime seasonal temperature changes, and these sudden fluctuations were similar to the northern hemisphere "explosive" warmings.

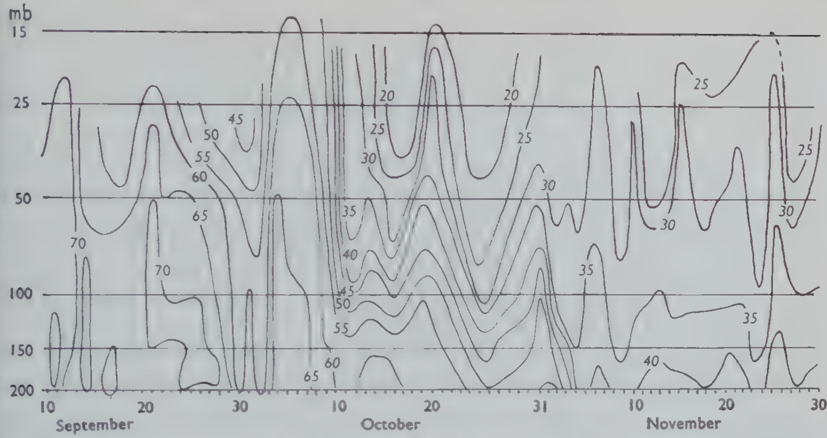

FIG. 2—Temperature-time Cross Section at Mirny, 1957. Temperatures in minus degrees Centigrade.

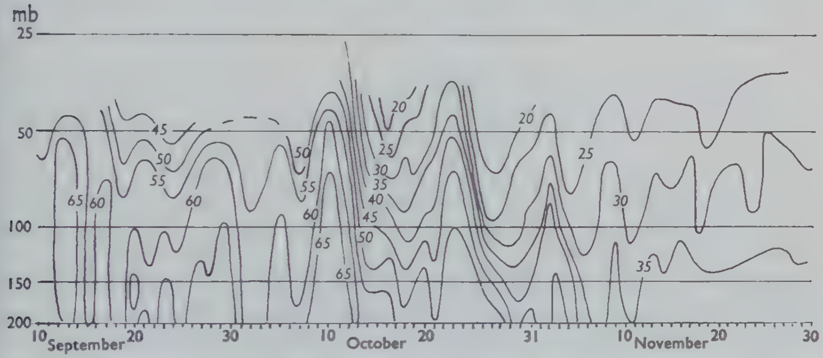

FIG. 3—Temperature-time Cross Section at d'Urville, 1957. Temperatures in minus degrees Centigrade.

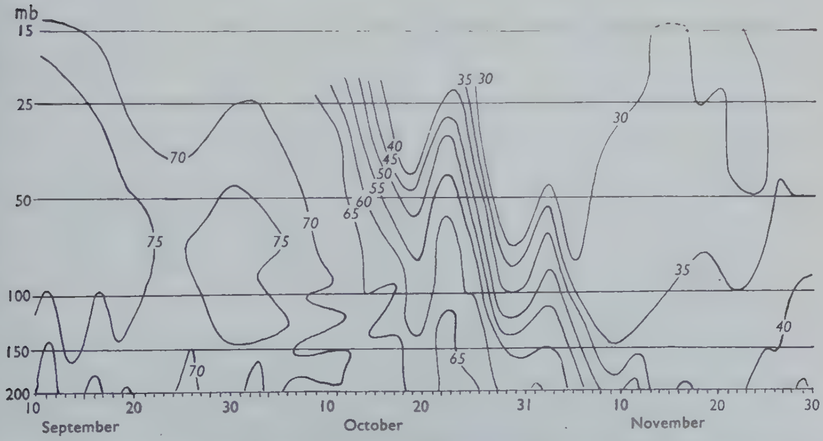

FIG. 4—Temperature-time Cross Section at McMurdo Sound, 1957. Temperatures in minus degrees Centigrade.

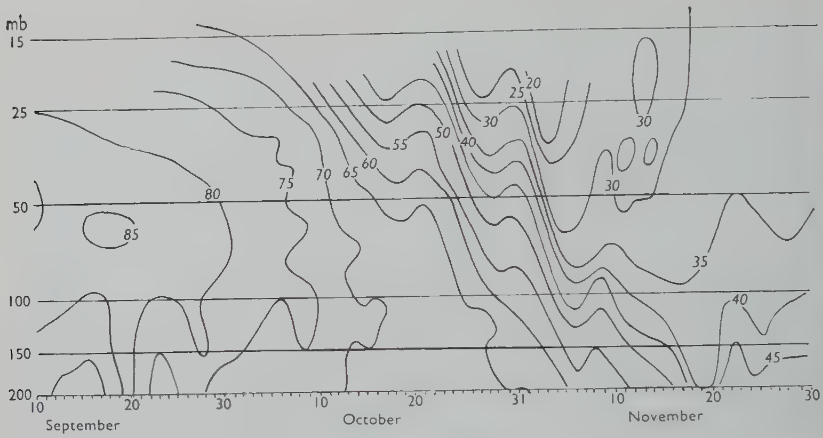

FIG. 5—Temperature-time Cross Section at Pole station, 1957. Temperatures in minus degrees Centigrade.

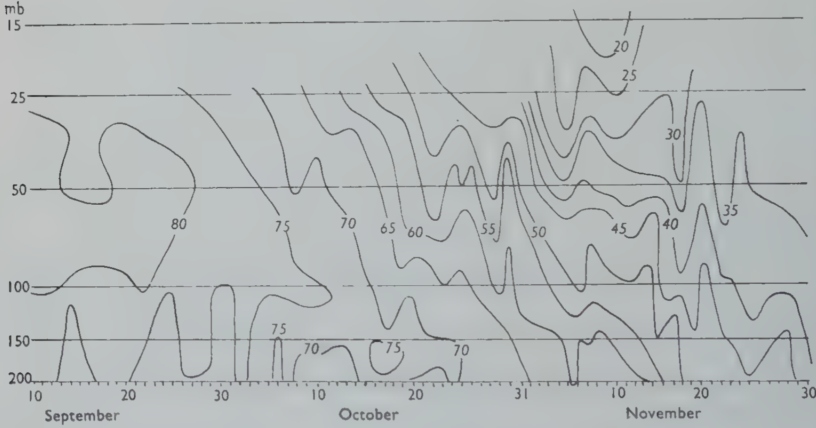

FIG. 6—Temperature-time Cross Section at Ellsworth, 1957. Temperatures in minus degrees Centigrade.

(2) The sudden temperature changes first started at the highest observed levels and spread downwards, gradually losing intensity, and reached the lower stratosphere in the late spring, after which the temperature fluctuations became small.

(3) Within the limits of accuracy of the cross sections the same phases of the temperature waves could be identified from station to station. There seemed to be a small lag in the west-to-east direction, changes at d'Urville following those at Mirny, and changes at Byrd Station following those at McMurdo.

(4) Temperature fluctuations appeared to be broader and less periodic over the Weddell Sea and Queen Maud Land than over the opposite side of the Antarctic at the same latitudes.

At the 50 mb level the net warming during the three spring months ranged from 30 to 50°C. It was less in the initially warmer coastal regions from Mirny to Hallett, and greater in the cold areas inside the polar night boundary. Interdiurnal temperature rises of 15° and falls of 10°C were the extreme values observed at this level.

In the spring of 1958 the net seasonal warming again was accomplished by a sudden quasi-periodic temperature change starting above the 25 mb level (approximately 23 km). Compared to 1957, the 1958 spring temperatures were lower throughout the season and their observed fluctuations were smaller and less regular. At the Pole however, a spectacular sudden warming was observed during 22 to 24 October between the 5 and 30 mb levels (approximately 34 and 21 km). At the 25 mb level the magnitude of this two-day warming amounted to about half of the seasonal temperature rise (Fig. 7).

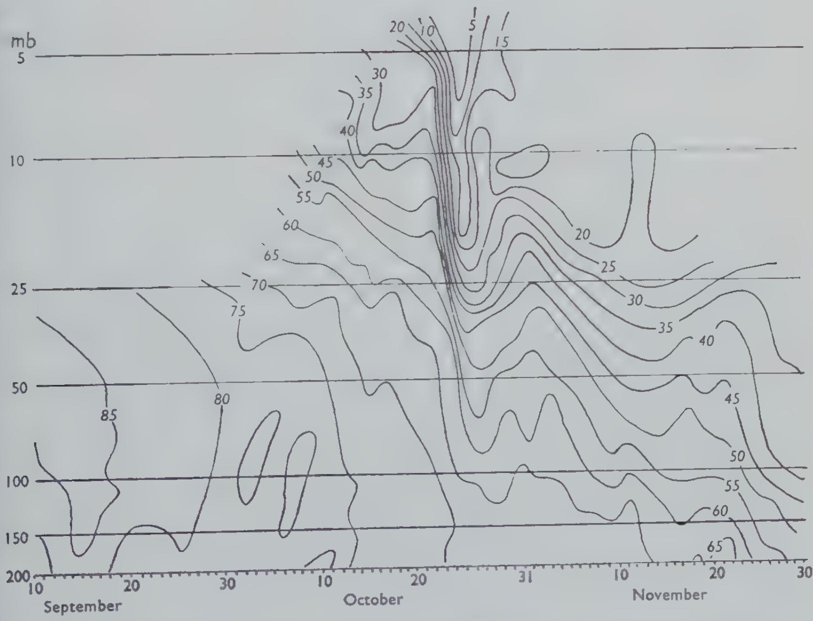

FIG. 7—Temperature-time Cross Section at Pole station, 1958. Temperatures in minus degrees Centigrade.

SYNOPTIC ANALYSIS OF THE CIRCULATION AT THE 50 MB LEVEL

The highest constant pressure level with sufficient information for synoptic analysis was the 50 mb surface, The sequence of 50 mb contour maps shown in Figs. 8–17 and 18–21 displays the circulation changes during the spring periods of 1957 and 1958 respectively. The dates of the maps were selected to coincide with the most pronounced temperature anomalies at this level. The most outstanding feature of the circulation during both September and October in both years was the persistence of the cold cyclonic vortex over Antarctica. Early in September of both years (Figs 8 and 18) this vortex

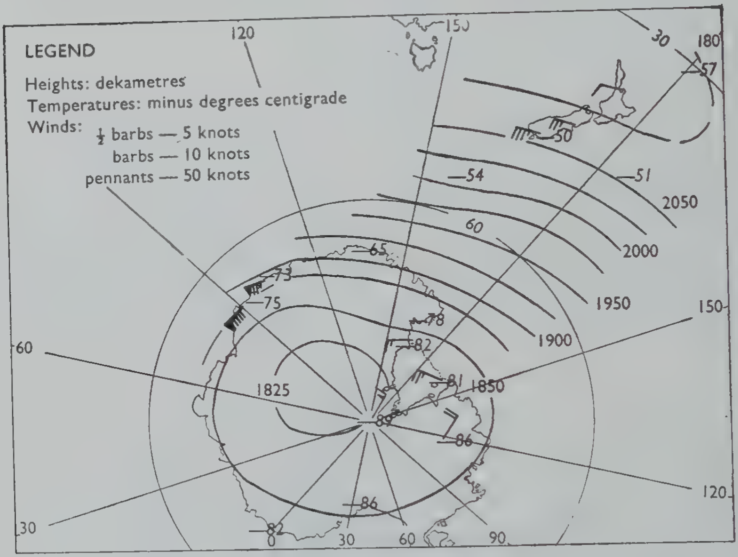

FIG. 8—50 mb Contour Map, 6.9.57.

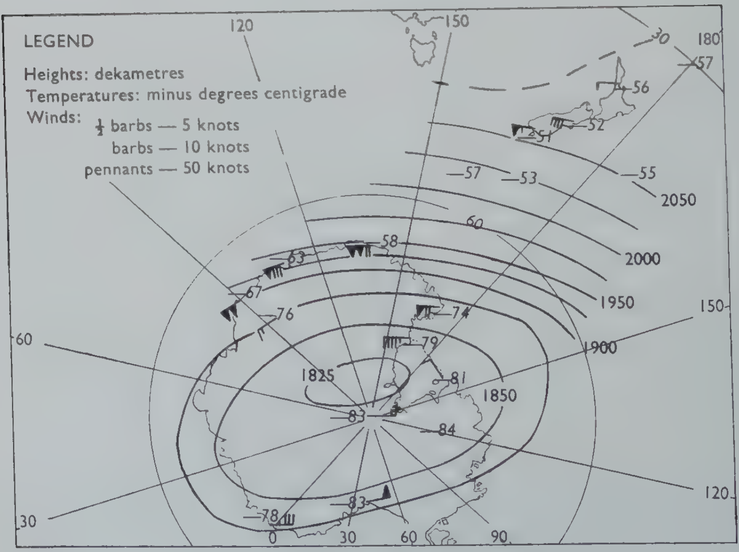

FIG. 9—50 mb Contour Map, 15.9.57.

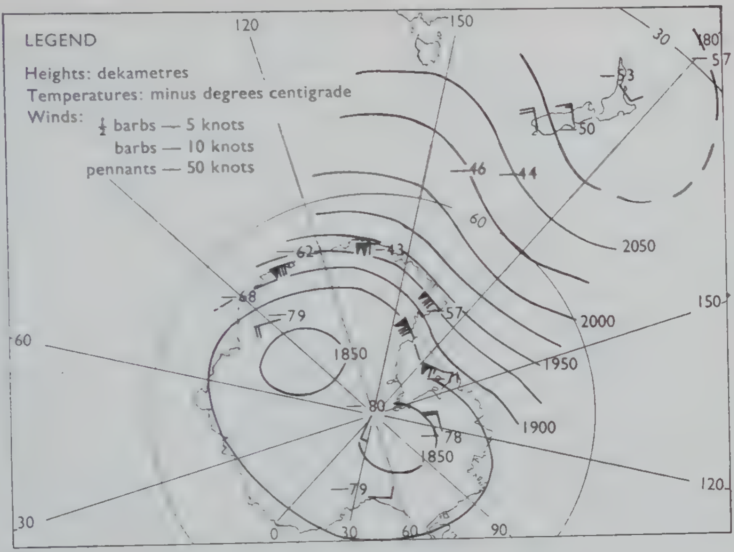

Fig. 10—50 mb Contour Map, 24.9.57.

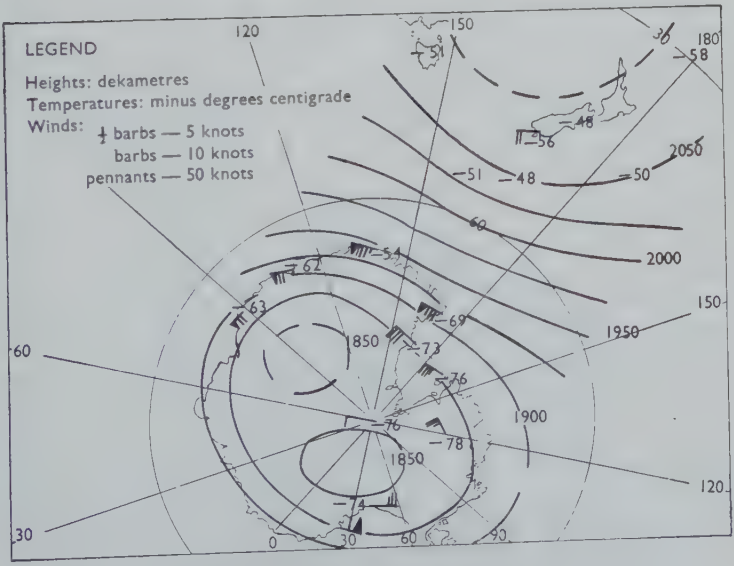

Fig. 11—50 mb Contour Map, 5.10.57.

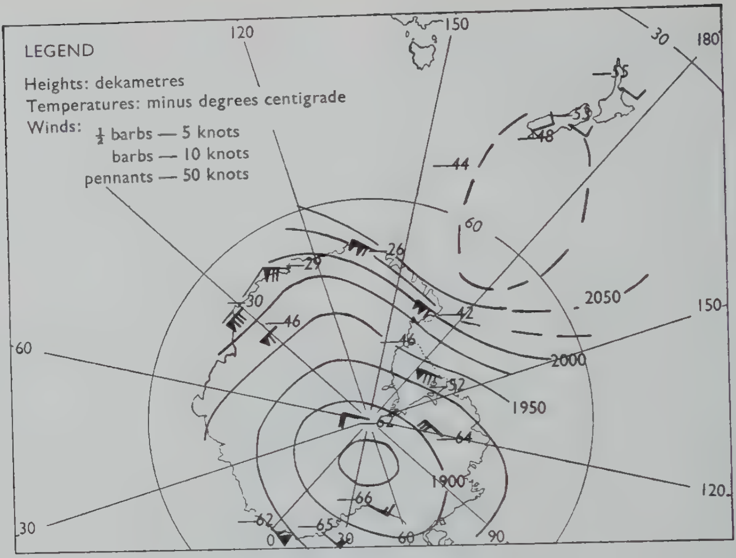

FIG. 12—50 mb Contour Map, 11.10.57.

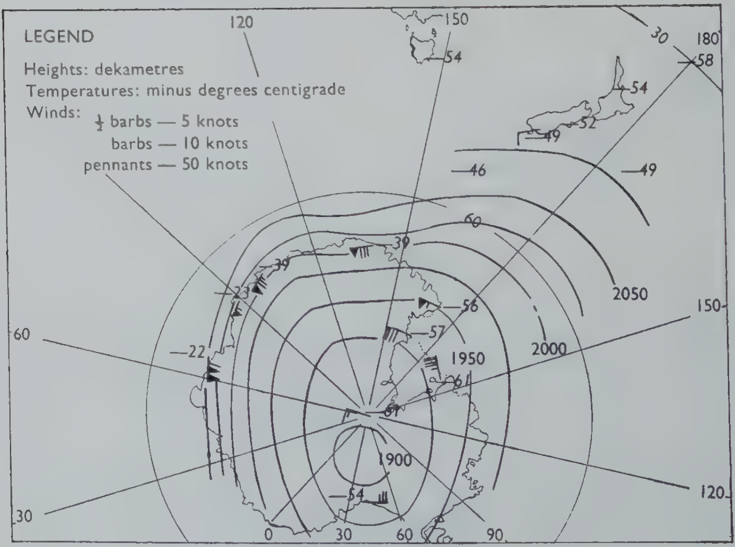

FIG. 13—50 mb Contour Map, 23.10.57.

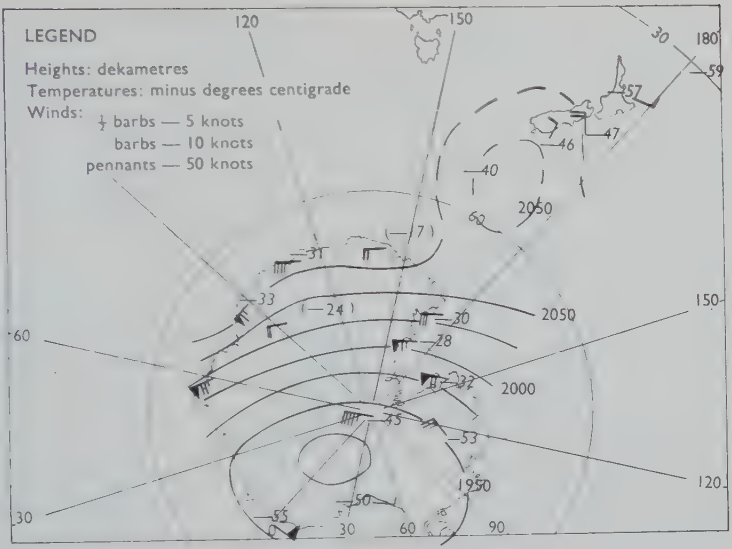

FIG. 14—50 mb Contour Map, 28.10.57.

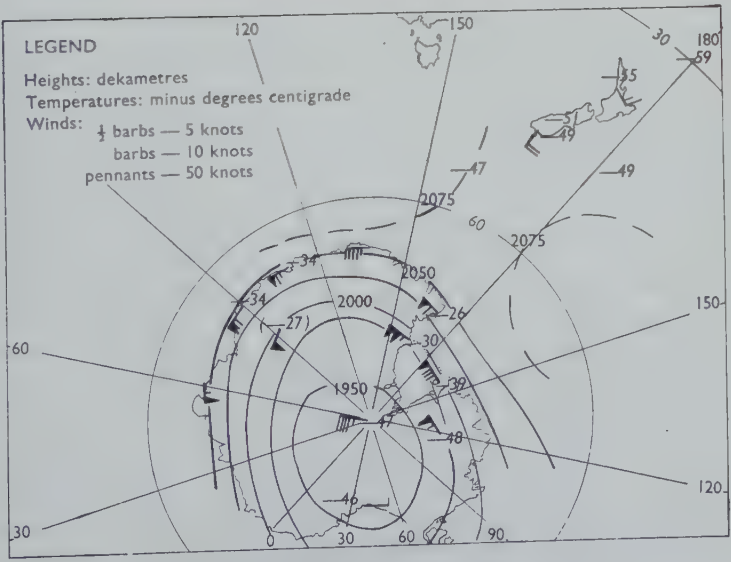

FIG. 15—50 mb Contour Map, 1.11.57.

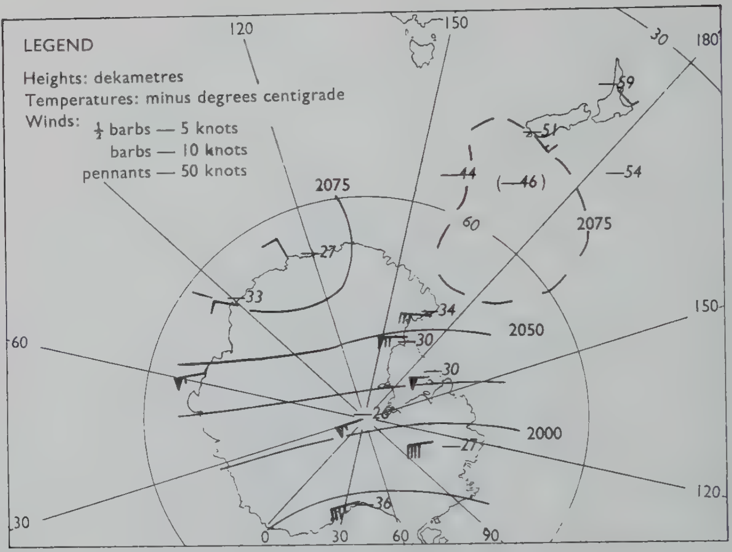

FIG. 16—50 mb Contour Map, 6.11.57.

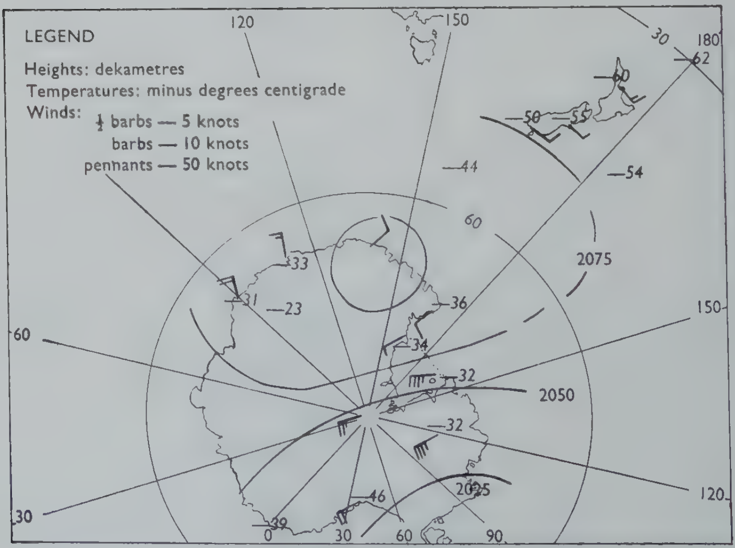

FIG. 17—50 mb Contour Map, 16.11.57.

appeared to be centred over East Antarctica some distance away from the Pole. The warmest temperatures occurred over d'Urville and over a wide latitude belt between d'Urville and southern New Zealand, and this was also the area that showed the first rapid warming, while the rest of Antarctica continued to warm at a very slow rate only (Figs. 9 and 10). A strong jet stream accompanied this development of strong horizontal temperature gradients, and the vortex centre appeared to have split into two. The circulation at the date of the peak warming at d'Urville in the last days of September 1958 is shown in Fig. 19 for comparison. The position and intensity of the polar vortex was similar in both cases. Fig. 11 shows the situation during the cooling period that followed the first warming over the same latitude zone at the beginning of October 1957. The temperature cross sections Figs. 2 and 3 show clearly that this cooling and the second warming started at Mirny a few days earlier than at d'Urville. By the date of Fig. 12 the second warming period had reached its maximum intensity, and the circulation showed again a single vortex centre situated over the area between the Pole and Ellsworth stations. It was weakening slowly, but changed its position little during the rest of the month. It is interesting to compare the situation in Fig. 12 with the circulation on 24 October 1958 shown in Fig. 20, which was the date when the maximum temperature at 50 mb. over d'Urville for the 1958 spring season occurred and was near the onset of the very intense warming at higher levels over the Pole. In both maps a strong ridge seemed to appear between the New Zealand and the Antarctic coasts, while the polar vortex centre retreated towards the Weddell Sea in 1957 and in the direction of Queen Maud Land in 1958. During the following third cooling and warming cycle in the last week of October 1957 (Figs. 13 and 14), this ridge gave way to a trough, followed by the formation of a similar ridge in the same area. The circulation showed similar features in 1958 although the periods between cycles were much longer. The fourth and final warming in the first week of November 1957 (Fig. 15) mainly affected the Pole and the areas towards the Weddell Sea at this level, with the result that the horizontal temperature gradient between the Pole and lower latitudes reversed, the circulation about the polar vortex broke down, and the small cold vortex centre moved northwards off the Weddell Sea coast (Fig. 16).

In the 1958 season the break-up of the polar vortex occurred later than in 1957, and the final disappearance of the cold centre from over the continent occurred only in the last days of November (Fig. 21).

In both years a polar cyclonic vortex dominated the circulation at the lower stratospheric levels also (Alt, Astapenko, and Ropar, 1959). In the troposphere the circulation tended to become more complicated with the appearance of smaller cyclonic cells. The coldness of the Weddell Sea side of Antarctica and the Argentine Island region, compared to the Adelie Land and Ross Sea areas, seemed to be a general feature of the stratospheric circulation in all seasons in contrast to the conditions in the troposphere, where no such semi-permanent cold or warm areas could be distinguished throughout the year.

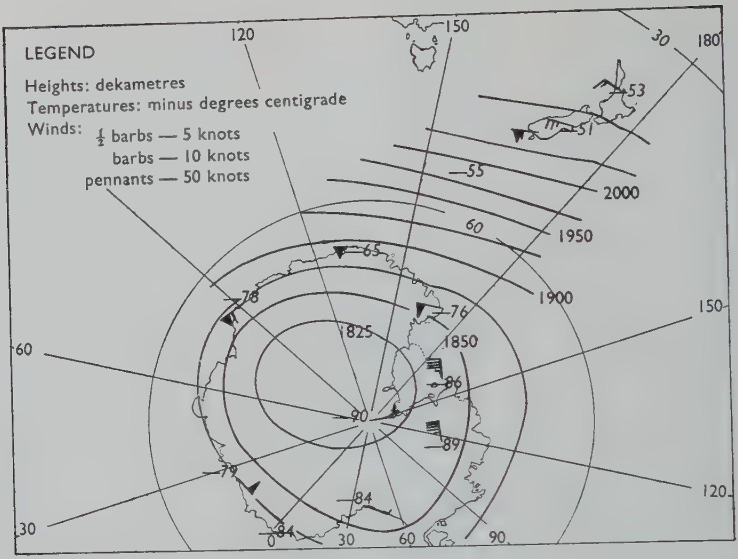

FIG. 18—50 mb Contour Map, 2.9.58.

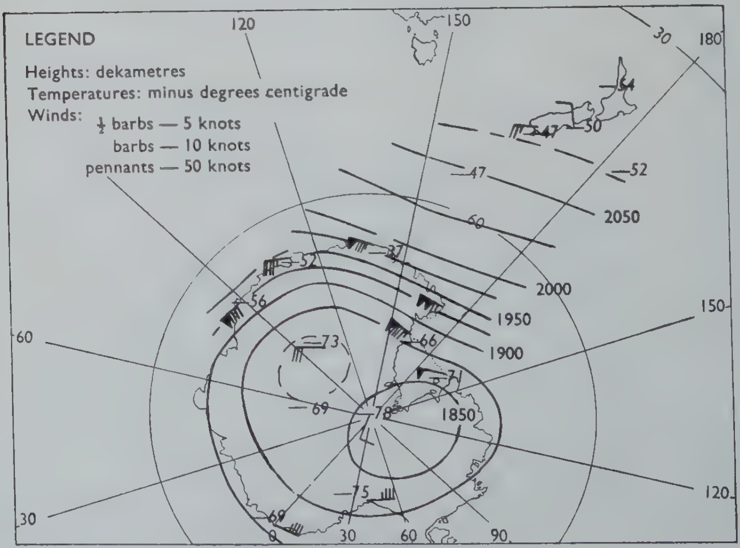

FIG. 19—50 mb Contour Map, 6.10.58.

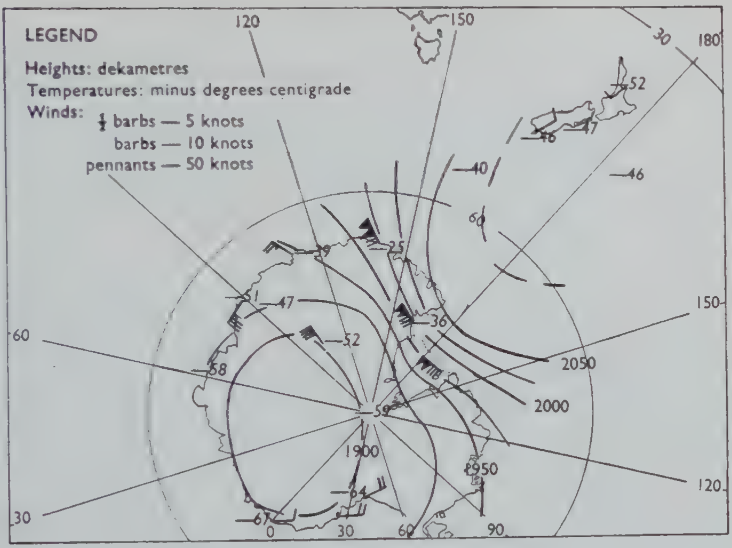

FIG. 20—50 mb Contour Map, 24.10.58.

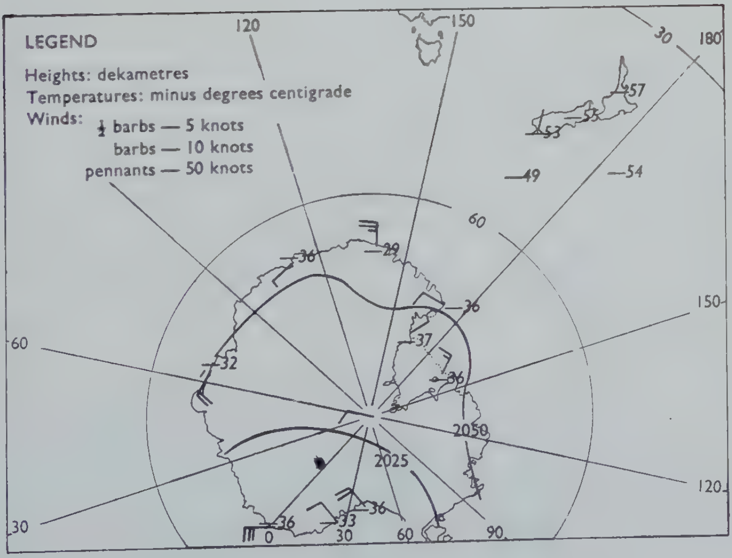

FIG. 21—50 mb Contour Map, 30.11.58.

Conclusions

The occurrence of large and sudden warming followed by downwards progressing quasi-periodic temperature fluctuations appeared to be the major process to establish the seasonal temperature reversal between high and lower latitudes in the springs of both 1957 and 1958. These large temperature anomalies first appeared at the coastal areas from Mirny to Hallett. Data at lower latitudes showed that the wide latitude zone north of these coasts to approximately 50° had similar temperature fluctuations and together with the coastal areas represented a semi-permanent warm zone during the breakdown of the winter-type circulation. The existence of this warm zone outside the polar night boundary agreed well with the latitudinal distribution of the total ozone amounts, which showed a zone of maximum ozone near 50° latitude during September and October. The cyclonic polar vortex typical of the wintertime stratospheric circulation dominated the 50 mb circulation throughout the spring seasons of both 1957 and 1958. After the appearance of the sudden large temperature anomalies between Mirny and McMurdo, the centre of the vortex slowly moved from East Antarctica towards the Weddell Sea by slightly different routes in 1957 and 1958 to become finally very small and move off northwards from that coastline, while a weak anticylonic summer-type circulation appeared over the rest of the continent. The separate roles played by radiation, latitudinal distribution of ozone, and the circulation at high stratospheric levels should all be taken into account in future research, as it seems that the seasonal stratospheric changes in the spring over high latitudes are brought about by the combined effects of dynamic phenomena and of radiational heating through the ozone layer.

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AMINO ACIDS AND PEPTIDES FROM SOME NEW ZEALAND FOSSILS

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Abstract

Extracts of six different types of fossil-bearing rocks of widely differing ages were shown by paper chromatography to contain amino acids. The presence of peptides in a lower Pleistocene siltstone was demonstrated by a biuret reaction. Similar extracts from seven rocks devoid of fossils contained neither amino acids nor peptides. The amino acids detected were: glycine, alanine, leucine, valine, glutamic acid, aspartic acid, proline and γ-aminobutyric acid, all of which are relatively stable to heat. Not all amino acids were present in each fossil. γ-Aminobutyric acid was present only in a trilobite limestone.

INTRODUCTION

Many of the organic compounds occurring in living cells are stable under the conditions prevailing over most of the terrestrial surface, provided that they are isolated from enzymic decomposition by micro-organisms. The presence of amino acids in various types of fossils, including even some Pre-Cambrian specimens, has been demonstrated by Abelson (1954, 1955, 1956, 1957a, and 1957b), while Erdman *et al.* (1956) have detected amino acids in Oligocene mud that is at present buried 5000 feet below the surface of the earth.

As the most important biochemical compounds are the enzyme proteins, the detection and identification of proteins and their degradation products in fossils offers an insight into paleobiochemistry. In particular it seems important to establish whether the structure of proteins from ancient organisms resembles that of their modern descendants. The evidence so far published indicates that the amino acid components of ancient proteins are all present in modern proteins, and that no novel amino acid has been identified from a fossil source.

The present experiments were conducted to investigate the amino acids and peptides of a series of New Zealand fossil-bearing rocks.

METHOD AND MATERIALS

Details of the rocks investigated are given in Table 1.

The rock samples were carefully cleaned to remove any possible surface contaminants. The rocks then were crushed mechanically and some fragments treated with hot, strong hydrochloric acid. The resulting solutions were decanted from insoluble residues, filtered, and passed through columns of ion-exchange resin (Zeo-Karb 215). Adsorbed amino acids were eluted from the columns by ammonia and the resulting solutions concentrated and tested for amino acids by the ninhydrin reaction.

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TABLE 1—Rock Samples

No.	Rock Type	Fossils	Locality	Period	Approx. Age (years × 10^6)
1	slate	graptolites	Cobb River, Nelson	Middle Ordovician	400
2	limestone	trilobites	Cobb River, Nelson	Mid-Cambrian	500
3	mudstone	*Buchia* and other molluscs	Kawhia	Upper Jurassic	130
4	tuff	*Inoceramus* and other molluscs	Upper Awatere Valley, Marlborough	Middle Cretaceous	100
5	limestone	algae	Buller River, Westland	Tertiary	30
6	siltstone	*Offadesma angasi* and other molluscs, foraminifera, etc.	Wairarapa	Lower Pleistocene	1
7	ignimbrite	none	Ohakune	Late Pleistocene	0·05
8	manganese quartz schist	none	Central Otago	Permian to Triassic	200
9	schist	none	Otago	Permian to Triassic	200
10	carbonaceous schist	none	Otago	Permian to Triassic	200
11	forsterite marble	none	Anita Bay, Milford Sound	Ordovician (?)	400
12	garnet schist	none	Toaroha River, Hokitika	Permian to Triassic	200
13	argillite from Alpine greywacke	none	Otaki Forks	Triassic (?)	200

To identify the actual amino acids present, the solutions were analysed by two-dimensional paper chromatography using a variety of solvents, including water-saturated phenol, collidine, *tert.* butanol–formic acid–water, and phenol–ammonia–water. Chromatograms were sprayed with 0·25% ninhydrin in butanol–water and the spots were developed at 40°C.

Extracts of the crushed rocks were made also with water, ethanol, neutral phosphate buffer, and saline. The resulting solutions, after filtration and concentration, were tested with ninhydrin and for peptides by the biuret reaction.

RESULTS

All extracts from fossil-bearing rocks gave a positive colouration with ninhydrin. The only rock sample containing biuret-positive compounds was the Lower Pleistocene siltstone (No. 6). The amino acids identified by paper chromatography of the extracts are listed in Table 2. Total amino acid contents of the rocks were estimated from the intensity of spots on the chromatograms as compared with known standards.

An unusual violet spot was observed on the chromatogram of the trilobite limestone extract (No. 2). This spot was tentatively identified as γ-amino-*n*-butyric acid. It could not be detected in extracts of the rock with extractants other than hydrochloric acid. The R_F values of this spot were 0·70 in phenol–water, and 0·25 in butanol–acetic acid–water (8-1-10). The addition of a small amount of γ-aminobutyric acid to the eluted limestone extract gave an intensification of the unidentified spot on the resulting developed chromatograms.

TABLE 2—Amino Acids of Fossils

Sample No.	Total Amino Acids (μM/g*)	Amino Acids Present
1	0·4	glycine, alanine, leucine, glutamic acid, proline, aspartic acid.
2	0·35	glycine, alanine, glutamic acid, γ-aminobutyric acid.
3	1·1	glycine, alanine, leucine, valine, glutamic acid, proline.
4	0·2	glycine, alanine.
5	1·4	glycine, alanine, leucine, valine, glutamic acid, proline, aspartic acid.
6	2·1	glycine, alanine, leucine, valine, glutamic acid, proline, aspartic acid.
7	–	none.
8	–	none.
9	–	none.
10	–	none.
11	–	none.
12	–	none.
13	–	none.

*Micromols per gram.

DISCUSSION

The results presented above demonstrate the presence in the six fossil-bearing rocks, and the absence in the other specimens, of amino acids. The amino acid concentrations observed in the present experiments are of the same order of magnitude as for the specimens investigated by Abelson. Only the Lower Pleistocene fossil contained peptides.

The question arises whether the detected compounds are the remains of proteins possessed by the organisms which formed the fossils, or are later contaminants. There is no *a priori* reason why the amino acids cannot be archaic. Individual amino acids are remarkably stable; alanine, for example, has a half-life at room temperature of about 3×10^9 years. Thermal decarboxylation is more rapid at higher temperatures; but unless there is evidence that a fossil has been exposed for long periods to high temperatures, there is good reason to suppose that its amino acids could survive indefinitely. However, some amino acids, notably serine and threonine, are relatively unstable. For this reason it is unlikely that intact proteins can survive within a fossil for periods of geological time. The decomposition of these unstable residues within protein molecules will give rise to a variety of peptides and free amino acids.

The question of the stability of amino acids under the more or less anhydrous conditions of many fossils is partially answered by the experiments of Fox *et al.* (1959), who have demonstrated that, contrary to expectations, temperatures of 180° to 200°C do not decompose dry amino acid mixtures, but promote extensive polymerization.

From the types and physical conditions of the rock samples used in the present study, it seems unlikely that any contamination by peptides or amino acids could have occurred from external sources. This view is supported by the analytical findings, which demonstrate the occurrence in the rocks of only those amino acids that are thermally stable over very long periods. If contamination had occurred, other amino acids would have been detected. The absence of peptides and amino acids from the volcanic and other unfossiliferous samples is further evidence for the absence of contamination *in situ*. Moreover, these results serve as a control on the analytical procedures.

The most interesting result is the probable presence of γ-aminobutyric acid in the trilobite limestone. Although this amino acid is known to occur in many modern organisms, including bacteria, fungi, higher plants, and animals (*see* Woiwod and Proom, 1950; Reed, 1950; Hulme and Arthington, 1950; and Awapara *et al.*, 1950), it has not previously been detected in fossil materials.* Until fairly recently γ-aminobutyric acid was not thought to occur in peptides, but Boulanger and Biserte (1951) have reported the presence of such a compound in brain tissues. No protein containing this amino acid has been reported. The present experiments indicate the presence of free γ-aminobutyric acid in the trilobite limestone. Whether this compound is of paleobiochemical significance, or is derived from glutamic acid by decarboxylation, is not known.

CONCLUSIONS

(1) A variety of amino acids has been extracted from six widely different fossil-bearing rocks.

(2) A Lower Pleistocene siltstone contains biuret-positive compounds: presumably peptides.

**Note added in proof:* J. D. Jones and J. R. Vallentyne (*Geochim. Cosmoch. Acta* *21* : 1, 1960) have recently reported the presence of γ-aminobutyric acid in subsurface sediments from Lake Opinicon, Ontario, and in a Green River shale from Colorado.

(3) The peptides and amino acids detected are probably archaic compounds and not later contaminants.

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ROCK-STRATIGRAPHIC NAMES FOR THE SOUTH ISLAND SCHISTS AND UNDIFFERENTIATED SEDIMENTS OF THE NEW ZEALAND GEOSYNCLINE

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Abstract

In the South Island the rocks deposited in the New Zealand Geosyncline of Late Paleozoic and Mesozoic age now form three main belts, non-schistose sediments lying both to the east and discontinuously to the west of a schist belt. For the non-schistose sediments of the eastern belt the name "Torlesse Group," derived from Haast's "Mount Torlesse Formation," which was used in a similar sense, is proposed. For the median schist belt the name "Haast Schist Group," named from the Haast River, is proposed, to embrace all the schistose rocks of the geosyncline.

INTRODUCTION

The greater part of the South Island consists of rocks deposited during a single geosynclinal phase, whose time of beginning is not clearly known but was probably in the Carboniferous or early Permian. Many of the rocks are now schists, but the times of sedimentation and of metamorphism of these rocks are far from certain. It is now commonly thought that the main axis of deposition of the "New Zealand Geosyncline" (Wellman, 1956) did not remain constant in position, and that tectonic movements within the geosyncline led to the cessation of deposition in it at different times in different places.

In the South Island the deposits of the New Zealand Geosyncline now form three main belts, non-schistose sediments lying both to the east and discontinuously to the west of a belt of schist. Fossils are fairly common in the western belt of sediments but are sparsely distributed in the eastern belt. Although they range in age from Permian to upper Jurassic, nowhere in the eastern belt has a sequence of fossils been described, and it is remarkable that few are known of ages between the restricted ages of the main fossil types—Permian (*Atomodesma*); mid-Triassic (Kaihikuan fauna); upper Triassic (*Monotis*); upper Jurassic (*Buchia*). *Terebellina*, probably little older than *Monotis*, is widely distributed. Although the decline of the influence of the New Zealand Geosycline is marked in Marlborough by upward transition in the Cretaceous from deeper-water (mainly redeposited) to shelf sediments, even the older Cretaceous sediments show some distinctions in lithologic characters that enable tentative sequences to be determined, commonly supported by sequences of fossils. In following these sequences stratigraphically downwards, however, there comes a point where no adequate distinction can be made from the bulk of the monotonous greywacke-dominated sediments deposited during the major geosynclinal phase. Although the degree of induration or metamorphism – the rank –

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generally increases with age, rocks of similar rank vary in age, this being best shown by the Permian to upper Triassic ages of sediments in the transition zone between schistose and non-schistose rocks.

Wellman (1952) introduced names for sedimentary facies within the rocks of the Geosyncline. Based apparently on type of deformation, relative abundance of fossils, and thickness of beds, the names "Hokonui facies" and "Alpine facies" were evidently intended to epitomise different sedimentary enviroments within the geosyncline. In 1956 Wellman introduced "shelf facies", "transitional facies", and "redeposited facies" in the Permian parts of the sequences, stating that in the Mesozoic part "Hokonui" represented the shelf and transitional facies and "Alpine" the redeposited facies. Recognition of sedimentary facies is a step in interpretation but gives little help in making clear the stratigraphic units. Moreover only broad generalisations with respect to the geosynclinal environments are possible without interpretation of the schists in terms of their original sedimentary facies. It may well be that the contrasts in internal schist structures between the schists of Otago and of the northern Alps are due, in part at least, to differences in original lithology.

The use of "metamorphic facies" indicating grades of metamorphism raises possibilities of confusion with the sedimentary facies, particularly as recently Coombs *et al.* (1959) introduced into New Zealand the term "zeolite facies" for rocks of a grade that includes most of the Permian-Jurassic sediments of "Alpine" or "redeposited" sedimentary facies. The schists fall within the greenschist and amphibolite metamorphic facies, biotite and chlorite zones being separately distinguished in the greenschist facies.* The chlorite zone itself has been subdivided into subzones on the basis of the degree of internal reconstitution and texture. The lowest-rank subzone, chlorite subzone 1, is almost impossible to distinguish on field criteria; the rocks show no schistosity, but the early stages of internal reconstitution within the chlorite zone can be recognised under the microscope. They are transitional between rocks that show neither microscopic nor macroscopic characters of chlorite zone rocks and those showing incipient schistosity (semi-schists).

This paper is concerned with the schist and with the eastern belt of sediments. The sediments were described as "Undifferentiated Jurassic-Triassic-Permian" rocks on the 1 : 1,031,760 New Zealand Geological Survey map (1947) and in the appropriate section (Willett, 1948) of the accompanying booklet. On the 1 : 2,000,000 New Zealand Geological Map (1958) and in the accompanying bulletin (Grindley *et al.*, 1959), they were described as "Undifferentiated greywackes", being distinguished by symbols indicating the age range. Both these maps covered the whole of New Zealand, and an age basis dominated the legends.

Although the present paper is concerned with the South Island, analogous problems of naming rock units arise also in the North Island; indeed it can be maintained that the broad similarities of sequences in the two islands should be emphasised by the use of rock-unit names common to both. This is for the future, however; the present need is for agreement on a satisfactory nomenclature for the practical problems that arise where the schists and "undifferentiated" sediments of the New Zealand Geosyncline extend continuously through several of the map sheets of the 1 : 250,000 series at present in preparation by the New Zealand Geological Survey. The greater part of the South Island forms the major region where these problems arise.

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*More recently Coombs (1960) has introduced a "prehnite-pumpellyite metagreywacke facies" that covers some rocks of chlorite subzones 1 and 2 as well as less metamorphosed rocks of higher rank than the zeolite facies.

1 : 250,000 MAPPING OF "UNDIFFERENTIATED" SEDIMENTS

The New Zealand Geological Survey's present 1 : 250,000 mapping programme allows greater flexibility in the legends than in recent smaller-scale maps. The first map in the new series to show the "undifferentiated" sediments was Sheet 21, Christchurch (Oborn and Suggate, 1959). A tiny area in Banks Peninsula was shown as undifferentiated Gore-Kawhia Series; a small area in the Canterbury foothills was shown as Balfour Series, because of the presence of *Terebellina*. This mapping followed the procedure of mapping in ages which is being used throughout the series of maps. The North Island Sheet 4, Hamilton (Kear, 1960) illustrates the compromise necessary where both "differentiated" and "undifferentiated" beds of comparable ages are mapped. Whereas time-stratigraphic stage subdivision of fossiliferous Kawhia Series beds was possible in the west, only "undifferentiated" Kawhia Series could be shown to the east, poorly fossiliferous beds of this age being described as Manaia Hill Group. In Sheet 2B, Barrier (Thompson, 1960) the age of the greywacke and argillite is so poorly known that its age range is given as (?)Maitai to Kawhia; it is described under Moehau Formation. Rock-stratigraphic names for the "undifferentiated" greywacke are also used on some at least of the other North Island 1 : 250,000 sheets, for example Sheet 8, Taupo.

In the South Island two main features require to be indicated: the presence of fossils of widely different ages, and the apparent continuity of the greater part of the "undifferentiated" rocks.

The continuity of the "undifferentiated" beds as a whole, their monotony, and the lack of known stratigraphic breaks, require to be immediately emphasised. The beds form a single rock-stratigraphic unit, and should be appropriately named. To show within individual sheets only a series of isolated areas, with their age or age range, and to omit any unifying rock-unit name would give a false impression of the stratigraphy.

1 : 250,000 MAPPING OF THE BOUNDARY BETWEEN SCHISTS AND "UNDIFFERENTIATED" SEDIMENTS

The boundary between chlorite subzones 1 and 2, roughly coincident with the change from non-schistose to semi-schistose greywackes, has been adopted as the mapping boundary between two major units. The essentially transitional character of the change makes the boundary—in common with all boundaries between rock units that grade into each other—arbitrarily defined at most places. Both microscopically and macroscopically, the most satisfactory type of rock for judging the degree of metamorphism is greywacke; argillite and volcanic rocks tend to show schistosity earlier than greywacke; greywacke that shows incipient schistosity falls within chlorite subzone 2 and is mapped as schist.

The chosen boundary between schists and "undifferentiated" sediments is reasonably satisfactory for field mapping, and accordingly forms a suitable boundary between named rock-stratigraphic units. If individual formations or members within the "undifferentiated" sediments could be traced continuously into the schists, rock units transgressing metamorphic boundaries would be needed. No such units have been recognised, and it is necessary to adopt units on the existing criteria.

1 : 250,000 MAPPING OF THE SCHISTS

The schists are to be mapped in terms of metamorphic zones and subzones. The only distinct rock-stratigraphic units recognised within them are belts of metamorphosed volcanic rocks, and these will be separately distinguished within the metamorphic zone into which they fall. Although recent mapping has revealed complex internal structures in the schists, no units suitable for mapping purposes have been described, and the metamorphic zoning provides the best subdivision at present.

The important considerations for naming the schists are in part similar to and in part different from those for naming the "undifferentiated" sediments. Regional differences in texture and internal structure in the schists can be more clearly distinguished than regional differences in lithology within the "undifferentiated" sediments, so that the modern regional names, especially "Otago" and "Alpine", which perhaps over-emphasise the differences, have more in common with sedimentary-facies names than with formation names. As a group of rocks, the schists have a unity imposed by their metamorphism. The schists of Otago and the Alpine regions grade into each other and no satisfactory boundary can be drawn. The schists of Marlborough are separated on an areal basis but have no specific characteristics that distinguish them. There is no doubt that when Harrington (1959, pp. 289–91) attributed "Otago Schist" to Benson (1921), and when Reed (1959a, pp. 18–9, and 1959b, pp. 223–4) attributed "Alpine Schist" to Wellman (1952) and "Marlborough Schist" to King (1939), they formalised, without defining, terms that were never intended to be other than informal and undefined. Benson clearly intended to refer only to the schist of the Otago region, and Wellman and King merely used the names Alpine and Marlborough respectively in map legends.

Yet, just as with the sediments, a single name is desirable by which to refer to the schists—as is clear from the use of "Otago, Alpine, and Marlborough Schists", for example, on the New Zealand Geological Survey's 1 : 2,000,000 map (1957) and in the accompanying bulletin (Grindley *et al.*, 1959). It is accordingly held desirable to use a single name for the schists as a whole, and to allow the recently-used regional names to lapse into a useful informal usage—for example, "Otago schists" as the schists of the Otago region—until such time as they are formally defined.

A ROCK-STRATIGRAPHIC NAME FOR THE "UNDIFFERENTIATED" SEDIMENTS

No attempt will be made to review fully the original definition and subsequent usage of names that have been used for parts, large or small, of the "undifferentiated" sediments. This has been done by various authors in the *International Stratigraphic Lexicon*, Volume 6, Fascicule 4, "New Zealand"; but it is advisable to refer also to the original authors.

The following names have been used:

Mount Torlesse; 1865	Embraces all the "undifferentiated" sediments of the Southern Alps and Canterbury foothills in the usage of Haast, who originally proposed it.
Maitai; 1873	First extended from the type area east of Nelson to cover some "undifferentiated" sediments of Canterbury by Hector, but even then probably in a time-stratigraphic rather than a rock-stratigraphic sense. It is doubtful whether there has been any rock-stratigraphic usage of Maitai for "undifferentiated" sediments during this century.
Kaikoura; 1874	Used by Hutton in the north-east of the South Island, except for eastern areas (probably mainly Jurassic) that he mapped as "Maitai" and younger.
Mount Potts; 1874	Applied by Haast to a section in the Mount Potts area, fossiliferous at two localities; or (Hector) restricted to the fossiliferous beds.
Wharfdale; 1884	Local name given by Hector to one particular formation.
Hokonui; 1885	Originally used by Hutton in a time-stratigraphic sense, the best known fossiliferous sequence at the time being in Southland. It has not been used in a rock-stratigraphic sense for the "undifferentiated" sediments. Since 1951 its use has been entirely time-stratigraphic (System), except that it was applied by Wellman (1952) to a sedimentary facies that specifically excludes the "undifferentiated" sediments.
Clyde River; 1904	Proposed by Park for a particular section north-west of Mt Potts. Later he abandoned it for "Aorangi".
Mount St Mary; 1904	Name introduced by Park for a sequence at Mount St Mary, fossiliferous in part.
Aorangi; 1910	Apparently restricted by Park to pre-Kaihikuan beds, within the Hokonui System.
Ida; 1933	Local name applied in Ida Range by Williamson.
Waihemo; 1934	Local name applied in Kakanui Ranges by Williamson.
Mount Robert; 1935	Local name of Fyfe, including (?) some semi-schists.

Haast's "Mount Torlesse Series" (later "Formation") was used by him to embrace all the beds in the South Island that have recently been called "Undifferentiated Permian-Jurassic" rocks. Its age range and subdivision were argued, somewhat acrimoniously, by Hector (1885) and Haast (1885). Haast maintained that there was a single formation, although he conceded that there might be a considerable range of ages; Hector maintained that there was enough fossil evidence to substantiate a considerable age range so that subdivision was justified. The present position is that the greater amount of fossil evidence now available gives an improved knowledge of the distribution of rocks of different ages, but that boundaries and relationships are not yet established. Indeed these will be established only by mapping in formations within the major unit that Haast recognised.

It may be contended that the name "Mount Torlesse" is too closely associated with the occurrence of the annelid *Terebellina*, formerly *Torlessia*, which is thought to be restricted in its age range. The association is largely through Hector's use of "Mount Torlesse" as a locality prefix to "annelid beds". Although "Mount Torlesse Annelid Beds" is listed by Adkin (1954) as a stratigraphic name, which has been perpetuated in the *International Stratigraphic Lexicon* (Grindley, 1959a, p. 254), this can scarcely be supported by referring to the three usages listed by Adkin. The first (Hector, 1886, p. xxx) appears to equate the particular annelid beds, located at Mount Torlesse, with Haast's Mount Torlesse Formation, which is not in keeping with Haast's own usage. The other two are locality names in fossil lists.

It is recommended that Haast's name be retained, but that "Mount" be omitted. Gordon (1890) used "Torlesse Slates" on a map legend for the "undifferentiated" sediments of the Mount Cook area, an area shown by Haast (1879) as Mount Torlesse Formation. There appears no justification for Grindley's (1959b, p. 409) equating Gordon's "Torlesse Slates" with the supposed formation "Mount Torlesse Annelid Beds" that he attributed to Hector.

The status of the unit is considered to be that of a Group, embracing the individual formations that are listed above, as well as all the remaining "undifferentiated Permian-Jurassic" rocks of the South Island east of the schist belt. Thus Haast's original usage is reinstated, the name being modified to "Torlesse Group".

In Marlborough the upper limit of the Torlesse Group is not everywhere easy to define. At Seymour Stream (Suggate, 1958) south of Trig. GZ, Jurassic (? basal Cretaceous) siltstone and indurated sandstone with "cannon-ball" concretions, which is unconformably overlain by the Split Rock Formation of Motuan age, is here assigned to the Torlesse Group. But elsewhere, as for example in the Coverham area (Wellman, 1955, p. 110), the apparent transition from "undifferentiated" greywacke and argillite to "Clarentian" beds prevents easy definition. It will be necessary to define formations carefully and decide whether they are best included in the upper part of the Torlesse Group or whether they should stand apart.

It has been noted above that the end of geosynclinal deposition differed in time from place to place, and the succeeding formations are not of uniform age. The oldest succeeding formations—the Cairn Range (= Malvern Hills = Wakaepa) and Clent Hills Formations—comprise sandstones, conglomerates, and shales containing floras of middle or upper Jurassic age (Edwards, 1934) that are inferred to rest unconformably (Speight, 1928, p. 8; 1938, p. 15) on greywacke here included in the Torlesse Group.

A NAME FOR THE SCHISTS OF OTAGO, THE SOUTHERN ALPS, AND MARLBOROUGH

The following list includes most of the names given to schists, with brief comments. Fuller descriptions are given by various authors in the *International Stratigraphic Lexicon*, Volume 6, Fascicule 4, "New Zealand" (1959), in which the original references are listed.

There are three main groups of names. The first (e.g., Lake Harris, Kurow, Glenroy) are names essentially used for local mapping, and only occasionally used beyond their original localities. Names of the second group (e.g., Maniototo, Kakanui) have been extended from local usage on a rank basis. Those of the third group (Otago, Marlborough, and Alpine) are modern regional names unrelated to rank.

Kakanui; 1865	Generally restricted to schists of chlorite subzones 2 and 3.
Tuamarina; 1874	Chlorite zone schists only, because higher rank schists are not present.
Wanaka; 1875	Generally restricted to coarsely-foliated chlorite zone schist.
Waihao; 1879	Schists of chlorite subzones 2 and 3, mapped by Haast as distinct from gneiss-granite (chlorite subzone 4, biotite and garnet zones); but not consistently mapped.
Lake Harris; 1881	Chlorite zone schists.
Cecil and Walter Peak; 1881	Low-rank chlorite zone schists.
Kurow; 1882	Schists of chlorite subzones 2 and 3.
Maniototo; 1906	Foliated chlorite zone schists, but extended to some metamorphic rocks of Nelson and Fiordland.
Awamoko; 1918	Almost synonymous with "Kakanui".
Glenroy; 1935	Schists of chlorite subzones 2 (?) and 3, biotite and garnet zones.
Otago; 1959 Marlborough; 1959 Alpine; 1959	Formalised without definition, in 1959, as regional names, based on earlier informal usages. Validity based presumably on undefined differences in character.

With the introduction of rank subdivision into zones and subzones over 20 years ago, the named rank-implying formations have been rendered too imprecise for retention. The regional names are unsuitable for application to all the schists because they have been used for purposes of contrast. The local names cannot be satisfactorily extended because the localities are clearly situated in one region or another, and because they are associated with only parts of the metamorphic range.

A new name is required to embrace all the schists produced by regional metamorphism of the rocks of the late Paleozoic – Mesozoic geosyncline and a name from an area not closely associated with the regional names is perhaps desirable. The name "Haast Schist Group" is therefore proposed. Approximately at the junction of the Alpine and Otago areas, the schists of the Haast River catchment embrace all the schist zones (Turner, 1933). Turner's recognition of oligoclase zone rocks to the west as well as to the east of the Alpine Fault does not detract from the value of the Haast section. The Haast Schist Group is intended to embrace all the schist formations listed above.

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POLLEN FROM DEEPLY BURIED COAL MEASURES, TARANAKI, NEW ZEALAND—No. 1

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Abstract

Five well samples from depths ranging from 10,700 to 13,040 ft were examined for pollen and spore content. The material graded from dull black coal or coaly mudstone to bright black coals below 12,450 ft. All yielded workable pollen floras, though there were fewer grains and species in the lower three samples. Pollen from all five samples indicates that the coal measures are of Late Eocene age, Runangan down to about 11,000 ft and Kaiatan below, to the bottom of the well at 13,040 ft.

Introduction

The object of this paper is to record pollen results from samples taken at a much greater depth than is normally accessible, and likely to be of value in future correlations over a wide area.

The samples were kindly supplied by Shell, B.P., and Todd Oil Services Ltd., from the Taranaki oil well designated Kapuni No. 1 (Fig. 1). Grid reference: N 119/753415. Details are as follows:

Depth (ft)	Nature of sample	Sheet Fossil No.	Lab. No.
10,700	Dull black coal with much fine mineral matter. Core	N119/518	L 1593
11,235	Bright black coal. Core	N119/519	L 1612
12,450	Bright black coal. Drill cuttings	N119/520	L 1641
12,905	Bright black coal. Core	N119/521	L 1642
13,040	Bright black coal. Drill cuttings	N119/522	L 1643

According to Dr van der Sijp (N.Z. Geological Survey Staff Conference, 1959): "Tertiary sedimentation in Taranaki started in the Earliest Oligocene or possibly Eocene. After deposition of coal-measure-like strata, presumably overlying the peneplained Mesozoic rocks, a carbonate shelf developed (Te Kuiti-Cobden Limestones), extending along the West Coast of both North and South Islands. At the time of deposition of the Mahoenui Mudstones (Upper Oligocene) the Taranaki area developed into a real basin".

Penetration of the coal measures as drilling of the oil well continued furnished the samples on which the present investigation is based.

The ranges of pollen and spores referred to in this paper are as set out by Couper (1960).

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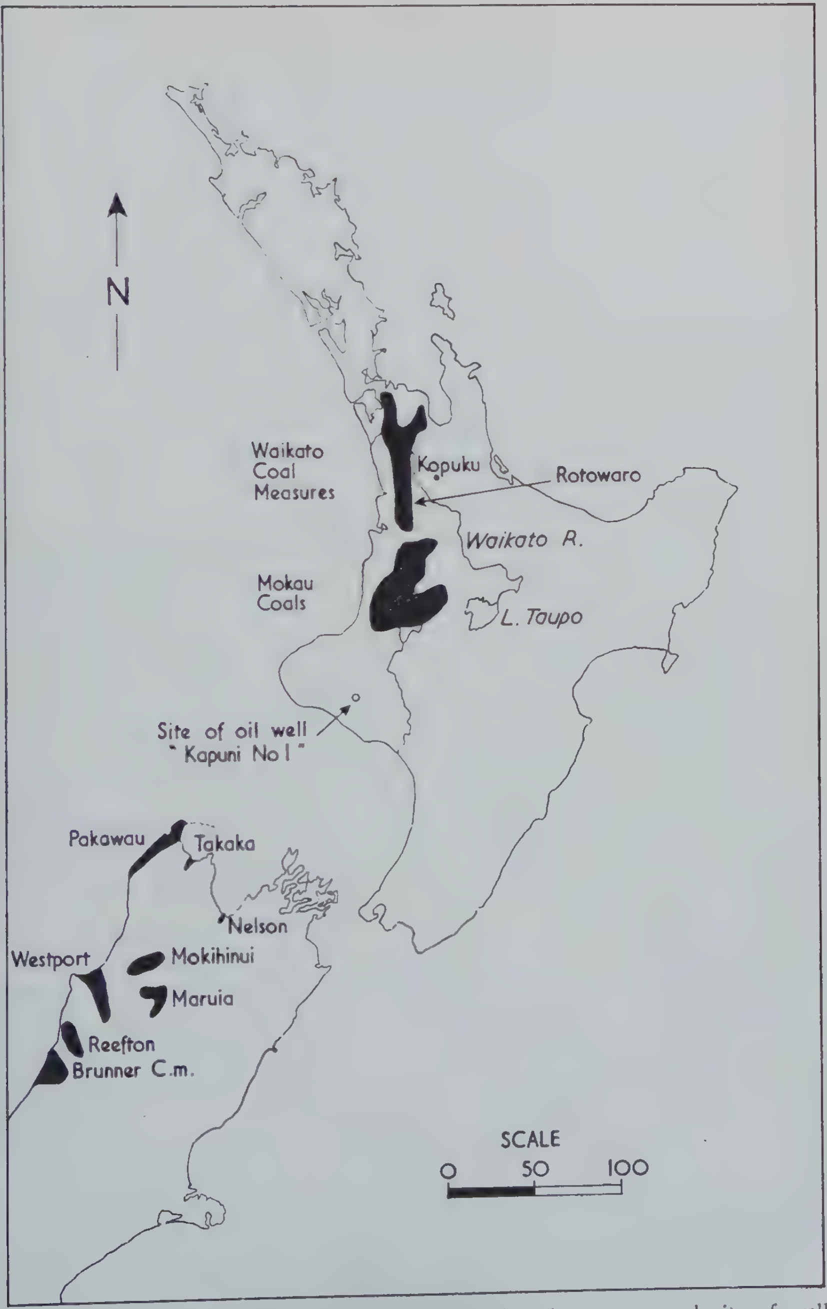


Fig. 1—Locality map, showing principal areas of coal measures and site of well. The scale is in miles.

POLLEN SPECIES

Some 63 pollen and spore types were recognised and, of these, 28 are species as yet undescribed. The species recorded are set out in Table 1. Angiosperms are arranged according to Hutchinson (1959).

TABLE 1—Pollen Identified from Kapuni No. 1 Well

Species	Samples in Which Present				
	L1593	L1612	L1641	L1642	L1643
Gleichenia sp.	,,				
Dicksonia aff. *squarrosa* (Forst. f.) Swartz	,,				
Cyathea sp.	,,	,,			
Phymatodes aff. *diversifolium* (Willd.) Pic. Ser.	,,	,,			
Ephedra notensis Cookson	,,				
Araucariaceae	,,				
Dacrydium aff. *cupressinum* Lamb.	,,				
Podocarpus aff. *dacrydioides* A. Rich.	,,				
Podocarpoid	,,	,,	,,		,,
Laurelia aff. *novae-zelandiae* A. Cunn.	,,				
Knightia aff. *excelsa* R. Br.	,,		,,		
Proteacidites annularis Cookson		,,	,,	,,	,,
P. cf. *crassus* Cookson		,,			
P. parvus Cookson	,,			,,	
P. cf. *rectomarginis* Cookson					,,
P. symphyonemoides Cookson	,,		,,	,,	,,
Metrosideros sp.	,,	,,			
Leptospermum sp.	,,				
Myrtaceae	,,	,,	,,		,,
Nothofagus flemingii Couper	,,		,,		,,
N. matauraensis Couper	,,	,,			
N. sp. (*fusca* group)			,,	,,	,,
Dysoxylum aff. *spectabile* (Forst. f.) Hook. f.					,,
Araliaceae	,,	,,			
Liliacidites intermedius Couper	,,				
L. variegatus Couper	,,	,,			
Phormium reticulatus Couper		,,			
Rhopalostylis aff. *sapida* Wendl. & Drude	,,				
Tetracolporites oamaruensis Couper		,,	,,		
Tricolpites matauraensis Couper		,,	,,	,,	,,
Triorites fragilis Couper		,,		,,	,,
T. harrisii Couper	,,	,,	,,	,,	,,
T. minor Couper	,,	,,			
T. scabratus Couper	,,				,,
T. spinosus Couper		,,			,,

AGE OF THE SAMPLES

L 1593, 10,700 ft

About thirty pollen and spore types were recognised, the most significant stratigraphically being *Nothofagus flemingii* Couper, *Rhopalostylis* aff. *sapida* Wendl. and Drude, and *Podocarpus* aff. *dacrydioides* A. Rich. *Nothofagus flemingii* occurs in many coal measures and other sediments classed as Arnold (including S44/763, S68/784, and S159/520). It is common in the Bortonian and Kaiatan stages but rare in deposits classed as Runangan. This latter stage is given as its upper limit by Couper (1960, p. 55), who, however, records specimens of it from N112/505 of Duntroonian age but considers that they may be derived from older sediments in the area. However, in the light of the present lack of Whaingaroan floras and the paucity of Duntroonian floras, it seems better not to limit the range of *N. flemingii* to the Arnold pending further work on marine-dated Whaingaroan materials. In L 1593 only two specimens of *N. flemingii* occur in a count of 328, and so on relative abundance a Runangan age would be consistent with what is at present known of early Tertiary floras.

Couper (1960) lists 72 samples from the Arnold Series and gives the first appearance of *Podocarpus* aff. *dacrydioides* and *Rhopalostylis* aff. *sapida* as Runangan, based on records from N52/639, N56/530, and N83/510. These are pollen types not easily overlooked, especially the former, and this seems fairly good evidence for Runangan, as delimited by Couper (1960), as the lower limit. *Nothofagus matauraensis* Couper is rather rare in the Bortonian and Kaiatan but is very common from then on. Couper (1960) states that in the Runangan to Duntroonian Stages "most of the Cretaceous conifers are either absent or very rare and their role as the forest dominant is taken over by *Nothofagus matauraensis* of the *brassi* group of southern beeches". The total conifer pollen observed was 5, as compared with 10 of *N. matauraensis.* Couper also states that "throughout the lower and middle Eocene, fern spores are comparatively abundant and the parent plants were probably important in the vegetation of that time". In this sample fern spores were of low frequency (1·5 per cent of the total).

The dominant pollen type in L 1593 is of the Myrtaceae, *Metrosideros* and genera now extinct in New Zealand although, as far as may be judged from pollen types, still represented in Australia. Next in order of importance were *Triorites harrisii* Couper and *Laurelia* aff. *novae-zelandiae* A. Cunn. *T. harrisii* may represent the Casuarinas, which were, from paleobotanical evidence, formerly represented in New Zealand, but survive to the present day only in the Australian and Polynesian regions. However, a close agreement between it and the New Caledonian *Canacomyrica monticola* (Myricaceae) has been noted by Cookson and Pike (1954).

L 1612, 11,235 ft

On stratigraphic position, if a Runangan age is accepted for L 1593, this sample should be Runangan or older and may even be so if a younger age is accepted for L 1593. On the first slide examined a count of 258 grains was obtained. Two more slides were searched for additional species, and also some good specimens which confirmed earlier identifications were found. On pollen results the sample was considered definitely of Arnold age. Five species indicate an Arnold age: *Proteacidites symphyonemoides* Cookson, *Triorites fragilis* Couper, *T. spinosus* Couper, *Tetracolporites oamaruensis* Couper, and *Phormium reticulatus* Couper.

The following points favour a Kaiatan age. Excellent specimens were found of *Phormium reticulatus,* which is known from at least ten localities, the oldest being Kaiatan (Rotowaro No. 3 and Rotowaro d/h, N56/631, 630). Specimens were also found which match well with *Triorites fragilis,* known from at least 13 localities ranging in age from Late Cretaceous (Mata Series) to Kaiatan, but rare in Arnold Series.

This sample is reasonably well established as Kaiatan on the ranges of the species available. The two species, *Podocarpus* aff. *dacrydioides* and *Rhopalostylis* aff. *sapida*, present in the previous sample, the latter as 1·5 per cent of the total count, were not found in this sample. *Nothofagus matauraensis* was also absent. The floras represented by L 1593 and L 1612 agree in the low frequency of both beech and conifer pollen, but differ markedly in other respects. In L 1612 ferns are slightly more abundant and comparatively fewer pollen groups are represented, but there is some diversity in two, the species of *Triorites* and of the family Proteaceae. With the change in vegetation from L 1612 to L 1593 there was also a change in the type of accumulation, the sample L 1593 being a less pure coal than L 1612.

A Kaiatan age for the sample L 1612 seems reasonably certain, both on time ranges of species and on relative abundance. When floras from the Rotowaro coals are compared, L 1612 is most nearly related, especially on relative abundance, to N56/630, dated by Couper as Bortonian–Kaiatan, though there are differences in the species lists.

L 1641, 12,450 ft

This sample gave a poor but workable flora of 12 species, with a total of 179 grains. Of these only four proved of significance stratigraphically. For discussion of the range of *Nothofagus flemingii*, refer to sample L 1593. *Tetracolporites oamaruensis* is recorded only from beds classed in the Arnold Series, and *Proteacidites symphyonemoides* and *Tricolpites matauraensis* first appear in the Bortonian and continue through the Arnold into younger sediments. These species then, indicate only that the sample is of Arnold age. *Nothofagus flemingii*, as mentioned previously, is generally common in the in the Bortonian and Kaiatan and rarer in the Runangan. Only two grains of *N. flemingii* were identified, and this could be taken to indicate a Runangan age but for the facts that *N. flemingii* is rare in all the samples examined from the bore, and the sample above (L 1612) is dated as Kaiatan.

A number of species of Myrtaceae are present but are not referable to present-day New Zealand species. It is possible, however, that they have affinities with species at present living in Australia.

The flora, as in the sample above (L 1612), is dominated by the long-ranging *Triorites harrisii* (56 per cent). Couper (1960) records that Bortonian-Kaiatan floras of the Waipara section are dominated by this species and that all other floras of a similar age have abundant *T. harrisii*. *Nothofagus matauraensis* is absent in this sample (L 1641) and is recorded by Couper (1960) as absent or poorly represented in most Bortonian and Kaiatan floras, but abundant in the Runangan. *Proteacidites annularis* is common in the sample and according to Couper is common in the Arnold Series but rare in Dannevirke and doubtful in Landon Series. On time ranges the sample is Arnold Series and on relative abundance and stratigraphic position Bortonian or Kaiatan Stage.

L 1642, 12,905 ft

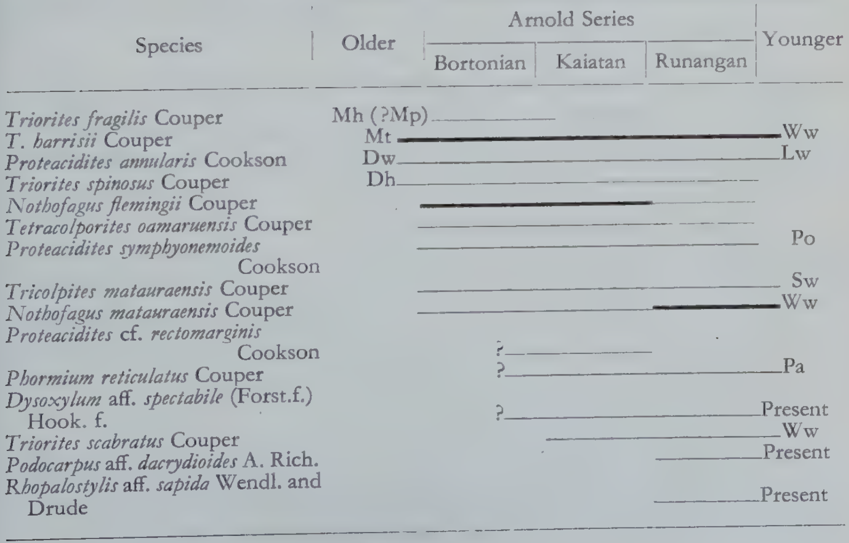
This sample is again dominated by *Triorites harisii* but is poor in total pollen (94 grains) and in species. With a Kaiatan upper limit for the sample above (L 1641), this sample must be Kaiatan or older. *Proteacidites* *symphyonemoides* and *Tricolpites matauraensis,* which first appear in the Bortonian, indicate a Bortonian lower limit. *Triorites fragilis,* which last appears in the Kaiatan in a number of localities, is fairly common, indicating the upper limit as Kaiatan. *Proteacidites annularis* is also present in the sample but *Nothofagus flemingii, N. matauraensis,* and *Tetracolporites oamaruensis* are absent.

By the evidence from the few species present, and from the sample above, a Bortonian-Kaiatan age is indicated. In his earlier work, Couper (1953) could not separate Bortonian and Kaiatan, and in his later study (1960) he still had difficulty, many samples being recorded as Bortonian-Kaiatan.

L 1643, 13,040 ft

Nothofagus flemingii is common in this sample, indicating the Arnold Series and on relative abundance Bortonian-Kaiatan Stages. *Proteacidites symphyonemoides* and *Tricolpites matauraensis* further indicate Bortonian Stage as the lower limit. *Triorites fragilis* is not uncommon, placing the upper limit as Kaiatan. One specimen each of *Proteacidites* cf. *rectomarginis* and *Dysoxylum* aff. *spectabile* (both known definitely in the Kaiatan and only doubtfully in the Bortonian) were recorded and further confirm a Bortonian-Kaiatan age. A number of specimens of *Triorites scabratus* were recorded, and as this species is not, as yet, known in sediments older than Kaiatan, this age is indicated for this sample and the three above. The flora was again dominated by *Triorites harrisii* (62 per cent), and characterised by the absence of *Nothofagus matauraensis.*

Table 2—Ranges of Dominant and Stratigraphically Important Species



Correlation of local series and stages with the international time-stratigraphic divisions may be set out as follows:

Lower Oligocene	Duntroonian Stage	Landon Series
	Whaingaroan Stage	
Upper Eocene	Runangan Stage	Arnold Series
	Kaiatan Stage	
Middle Eocene	Bortonian Stage	

For a description of these stratigraphic units see Fleming (1959).

Discussion

The floras from these Taranaki coals are generally very similar to most Arnold floras but they have lower percentages of beeches and conifers. The high percentage of Myrtaceae in L 1593, as compared with similar floras elsewhere, could most likely be explained by local differences in climate and vegetation or a different period of deposition within a stage, but until more detailed work on a number of areas can be done this cannot be confirmed. The sample L 1593 is very similar to coal samples from Kopuku (N52/635–640), dated as Runangan by Couper (1960), in species present, but the Kopuku samples have much higher percentages of *Nothofagus mataurαensis*.

It will be important, as opportunity offers, to compare these Taranaki coals more fully with the Waikato Coal Measures north of Taranaki and with the Brunner and quartzose coal measures of North Westland and North-west Nelson, all of which are apparently very similar in age. All these coals were presumably deposited along the margins of a presumed west coast synclinal basin in Middle Eocene to Lower Oligocene times, and it is not unlikely that the Taranaki coals are a southern continuation of the Waikato Coal Measures. The Taranaki coals are overlain by Whaingaroan marine sediments (Geiger, pers. comm.), as are many of the Waikato, Nelson, and Westland ones. While not necessarily all laid down at the same time, they are clearly parts of a sequence of coal measures deposited before marine transgression occurred, with depositon of Lower Oligocene marine sediments.

Acknowledgments

The writers are grateful to Shell, B.P., and Todd Oil Services Ltd., for the opportunity to examine this interesting material, and for permission to publish the results of the investigation.

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AN IMPROVED PORTABLE CONDUCTIVITY SALINOMETER FOR SEA-WATER SAMPLES

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Abstract

An instrument designed primarily for the field measurement of the salinity of estuarine water by the conductivity method has been improved for use on deep-sea-water samples. The instrument was converted to laboratory use and the sensitivity increased by elimination of the temperature-measuring section and the fitting of ten-turn rheostat controls. Compensation-control was introduced, enabling a reading to be taken which is automatically corrected against an accurate standard by a transfer method. The improved circuit is described. The suitability of Copenhagen standard sea water and possible sources of error in the measurements are discussed. Results indicate that the instrument, which can now be read to $0{\cdot}003\,^0/_{00}$, is reliable to at least $\pm 0{\cdot}01\,^0/_{00}$.

INTRODUCTION

The temperature-chlorinity meter described by Hamon (1956) was designed primarily for work in river estuaries where salinity and temperature differences are high and where great accuracy is not essential. When deep-sea samples are measured the required accuracy is generally of the order of $0{\cdot}01\,^0/_{00}$, and it was therefore necessary to examine the instrument and its mode of use with a view to reducing the errors present.

The original instrument consisted of a 3000 c/s oscillator supplying a Wheatstone bridge and a balance-detector with a galvanometer indicator. The measuring cell for salinity formed one arm of the bridge and a thermistor the second arm. The thermistor served to compensate for the effects of temperature variation on the cell. For temperature measurement the cell was switched out of circuit and only the thermistor used. The complete probe was suspended from an 80 ft length of cable. The temperature and salinity ranges were 0–30°C and $0\text{–}37\,^0/_{00}$ respectively. To obtain accurate results the readings were compared with measurements on a reference sample of known salinity (Copenhagen standard water). Any differences in salinity from the known value were applied as corrections to the readings.

In Fig. 1 the circuit of the instrument is shown in its modified form. Before dealing with the modifications made, however, it is proposed to discuss the validity of the use of standard sea water and other possible sources of error in conductivity measurements.

SUITABILITY OF STANDARD

As far back as 1925 the use of Copenhagen standard water for conductivity measurements was criticised by Knudsen (1925) because of the possibility of solution of silica from the glass. More recently, King (1950) found very thin fragments of siliceous material in an ampoule

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of P9 (1928) standard sea water. Suspended fragments, however, were not the only form in which silica was present. Some glass had apparently been hydrolysed by the water. King found 20, 4·4, and 2·5 mg/1 of dissolved silica in samples of standard water 22, 11, and 5 years old respectively.

The presence of dissolved glass in Copenhagen standard water would give low salinity readings by the transfer method. Extrapolating from King's figures a 3-year-old ampoule would have a dissolved glass content of say 1·5 mg/1, the increase in density causing an error of only $-0{\cdot}0015\,^{0}/_{00}$ in the salinity. Results from the standard Mohr titration in which the silicates are precipitated after the indicator has changed colour would not be affected by the increase in density. In any case the change in conductivity would be smaller and can be neglected if measurements are made to an accuracy of $0{\cdot}01\,^{0}/_{00}$. Copenhagen standard water should therefore be acceptable as the reference standard.

SOURCES OF ERROR

Errors from a number of sources can affect the determination of salinity by the conductivity method. The following sources of error have been examined:

(1) cell fouling; (2) polarisation; (3) poor null points; (4) poor temperature compensation; (5) mechanical defects in construction; (6) contamination; and (7) evaporation.

(1) *Cell Fouling*

Sea water is heavily contaminated by organic matter. Electrodes for conductivity measurements are therefore extremely susceptible to fouling by marine debris and bacterial slime. After a sample has been taken there is usually a rapid increase in the concentration of bacteria owing to mortality of other organisms, principally plankton, and also to the increase in temperature that usually takes place. The exact nature of fouling is not known, but it seems that intermittent adhesion of bacteria to the electrode surface causes a variation in the area of active surface and consequently leads to instability in the readings. Marine bacteria are extremely hardy. ZoBell and Brown (1944) report that only combined concentrations of 0·5% phenol and 0·5% chloroform were successful in permanently inhibiting bacterial growth in sea-water samples. Such chemical bactericides cannot be employed in samples for salinity determinations.

To pressure-filter every sample would take up much time and produce aeration. Experimental pressure filtrations gave variations of as much as $0{\cdot}1\,^{0}/_{00}$ in salinity between successive determinations. Radiation with 1650 Å ultraviolet light would be ineffective owing to the inability of these rays to penetrate the bottles. Addition of organic poisons caused either staining of the electrodes or precipitation of sodium chloride. A small amount of preliminary filtering could be effected by running the samples through a piece of nylon mesh (120–200 threads per inch) wrapped round the taps of the sampler devices. A stirrer in the sample under test tended to redistribute the adhesive bacteria continuously and thereby stabilised their effect.

(2) *Polarisation*

Polarisation occurs as a positive resistance at the electrodes. It can cause errors that are regular in behaviour in so far as they are dependent on the state of platinisation of the electrodes. The platinised layer will be slowly washed away with use until the cell resistance rises to a prohibitive level. Over-platinisation also causes a positive resistance that can change suddenly by the falling away of flakes of platinised platinum. The optimum degree of platinisation is given by Jones and Bollinger (1935): for the cell used in the present determinations 6 coulombs/cm^2 was found to give satisfactory platinisation. The maximum error due to polarisation, determined by the frequency change method of Jones and Bollinger (1935), amounted to 0·007$^0/_{00}$ of salinity for the correctly platinised cell.

(3) *Poor Null Points*

Poor null points can occur for a variety of reasons. They may be due to inadequate flushing of the cell. Further difficulties can arise if the thermistor current is too high and heats the water around the thermistor. These effects were minimised by stirring the sample. The oscillator frequency drifts for several minutes after switching on, and measurements should not be made until stability is reached (after a period of approximately 20 minutes). Dorrestein (1954) developed a method of compensation with a thermistor (negative temperature coefficient resistor) in order to prevent errors due to the reading of and correction for temperature. Sea water has a negative temperature coefficient, and in Hamon's instrument the thermistor was therefore placed in another arm of the bridge to cancel out the temperature variations (Fig. 1). Over limited ranges of temperature the thermistor can be adjusted with ordinary resistors to have properties closely resembling those of the measuring cell. Thermistors are known to be very sensitive to conducted and convected heat, but very much less sensitive to radiant heat. The operator's body heat therefore has little effect on the cell.

Instability in thermistors has been noticed, but found very small. Infrequently a sudden drift over a large range of salinity within a few minutes may be encountered, ascribed to thermistor instability. This effect, however, is immediately noticed. Some degree of artificial ageing might be obtained by heating in an oven or passing a high current, but no quantitative data are available on the effectiveness of such a treatment.

(4) *Poor Temperature Compensation*

Determinations of conductivity should normally be made in a laboratory where large changes in temperature are not often encountered. It was found that when the compensation control was set at the temperature of the substandard sea water sample (a value between 12° and 23°C), and the sample was less than 1°C different in temperature from the substandard, no additional temperature correction was necessary.

(5) *Mechanical Defects in Construction*

In the particular commercially available version of the temperature-chlorinity meter, irregularly wound rheostats had been used, the least increment of which was comparable to an error in salinity of 0·03$^0/_{00}$

in parts of the range. The indicating galvanometer could not be manually adjusted for zero and was rather small and awkward to read. Contact resistance in the switches and the necessity for visual interpolation of the direct reading dial could often be suspected of causing errors.

(6) *Contamination*

Contamination of a sample by the remnants of the previous one in the cell is small. The maximum amount, caused if two subsequent samples are at the ends of the range is $0{\cdot}006\,^{0}/_{00}$ per 0·1 ml of remnant. If the cell is flushed with part of the new sample and salinities are measured in order of collection—when large differences can be avoided—contamination is negligible.

(7) *Evaporation*

Wüst (1932) discussed at length the effect of storage on salinity samples and concluded that with full bottles stoppered with waxed corks and stored for several months, no more than the equivalent of $0{\cdot}002\,^{0}/_{00}$ increase in salinity occurred. Thompson (1940) also found an increase of less than $0{\cdot}005\,^{0}/_{00}$ and further mentioned that the bottles can be left open for a period of four hours without giving rise to any measurable change due to evaporation.

CIRCUIT CHANGES

In order to adapt Hamon's instrument to laboratory use and to improve its sensitivity, several changes were made, the chief of which were in the bridge circuit (Fig. 1). The temperature-measuring section and all range controls were removed so as to reduce contact resistance in the switches and make room for the "compensation" control. The "fourth" arm of the bridge (R6) was removed from the plug, fitted inside the instrument, and converted to a potentiometer. The setting of this rheostat with the aid of a standard sample thus compensates for any drift in the cell, so that it is not now necessary to note and apply corrections to the final read-out figure. This control also indicates the state of platinisation of the cell: when standardisation can be effected only by moving the control in the positive region replatinisation is necessary. The compensation control must have a least increment matching that of the salinity potentiometer and a ten-turn Helipot was used. All turns but one were locked. The salinity potentiometer was also replaced by a 200-ohm Helipot and a 50-ohm resistance fitted in series to eliminate the lower end of the range of measurement. Both Helipots were shunted and matched to effect smooth operation over the desired range of $31\text{–}37\,^{0}/_{00}$ salinity. The indicating galvanometer was replaced by a 30-0-30μA type with larger scale. The 40-ohm resistor in series with the meter acts not only as an overload protection when the cell is not immersed, but also governs the speed of travel of the meter needle. Its value is a compromise between the requirements of these two criteria. The resistor R1 was increased from 100 to 200 ohms to lower the voltage applied to the bridge, since the increased sensitivity now permitted detection of heating effects in the thermistor,

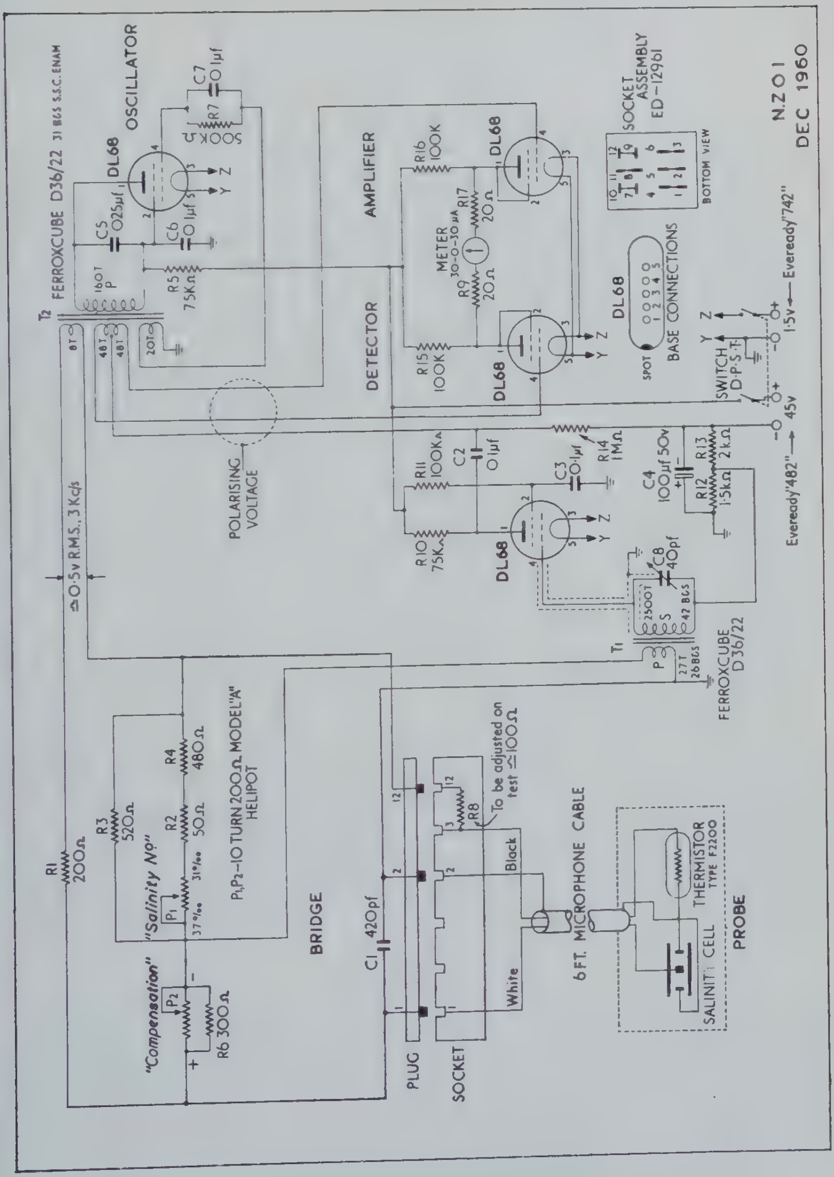

FIG. 1—Circuit of modified portable salinometer.

which were not formerly noticeable. The capacity unbalance caused by reducing the cable length from 80 to 6 ft was eliminated by reducing the capacitor C1 to 420 pF.

RECALIBRATION

The value of the resistor (R8) in series with the thermistor can be calculated using the formula given by Hamon (1956), but the resistance of the thermistor itself is given only to ± 20% by the makers. Although R8 is of the order of 100 ohms the precise value required had to be measured. The probe was immersed in a sample of known salinity and the bridge balanced. A resistance box was substituted for R8 and adjusted in steps of 10 ohms between 70 and 120 ohms over a range of temperatures between 13° and 23°C. The bridge was balanced for each reading and apparent salinities read, the compensation control being left untouched during the whole operation. Differences from the salinity value at 17·5°C were plotted for each resistance value (Fig. 2) and the value most suited

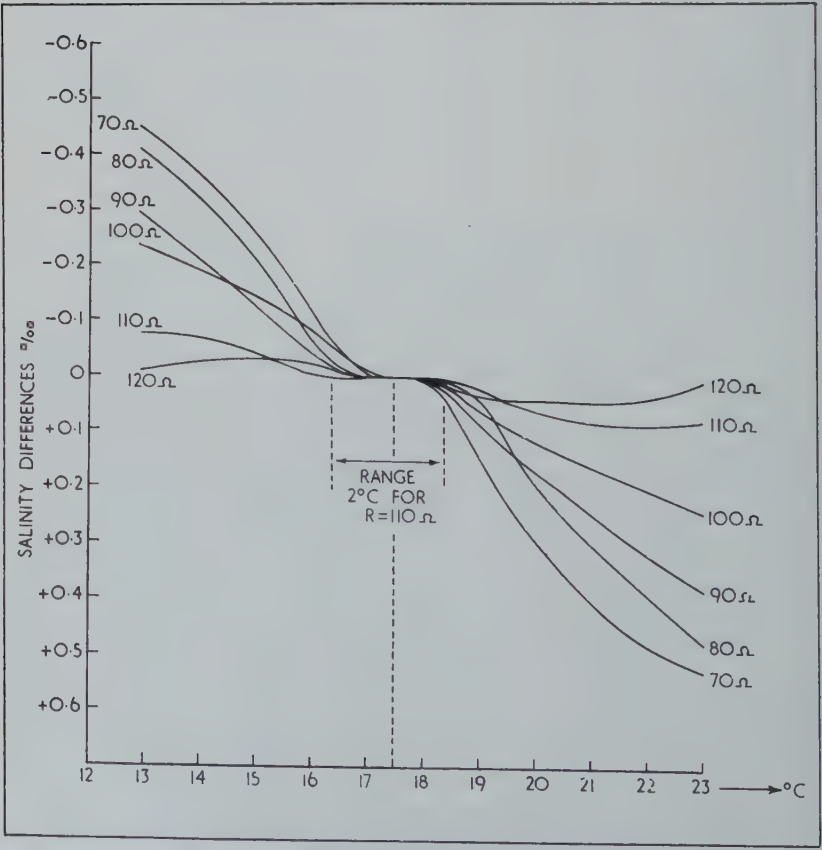

FIG. 2—Graphical determination of thermistor series resistance. Compensation control set at 17·5°C.

for the particular cell and thermistor interpolated between the curves. The instrument was then calibrated with a range of samples made from sea water diluted with distilled water and from partly concentrated sea water. The salinities of these samples were measured on an induction-type salinometer to an accuracy of ±0·003‰.

USE OF SUBSTANDARD

Since high accuracy can be obtained only by using the meter as a transfer instrument, comparing every few measurements with an accurate standard, large volumes of standard water are required. This requirement can be met by the use of a secondary standard or substandard whose salinity has been accurately determined. Sea water was collected from the Hikurangi Trench at 2500 m.* The salinity of this water is conveniently close to that of Copenhagen standard water and it also has a low bacterial content.

To reduce the multiplication of bacteria thymol was added at the rate of 0·25 g/l immediately after collection. On arrival ashore the sample was filtered through 200-mesh nylon and a plug of cotton wool and stored in glass carboys, which were painted to prevent light penetration and growth of organisms. The densities of this substandard and of Copenhagen water were then measured with the suspended plummet instrument of Gilmour (1958), and the salinity of the substandard determined by comparison. The density of the substandard was rechecked by this method at monthly intervals. A small rise of approximately 0·02° ‰ in salinity, due to evaporation, was noticed after each six months. A check on the suspended-bacteria content of the water was carried out and the results were as follows:

Samples from 1000 and 2500 m of depth, freshly drawn: < 100 bact./ml.
Sample from 1000 m, stored with thymol for 24 hours: 32,000 bact./ml.
Sample from 2500 m, stored with thymol for 6 months: 42,000 bact./ml.

It would seem that the amount of thymol added was insufficient (perhaps also qualitatively inadequate) to arrest bacterial growth in the stored water samples. Such a reproduction of organisms in samples in small containers is believed to be enhanced by the large surface area compared with the enclosed volume.

CONCLUSIONS

Apart from the attainment of higher sensitivity and accuracy, the instrument as converted has been found much easier to handle and to be stable in operation. Approximately 30 samples can be measured per hour. A check on a number of marked samples, randomly distributed amongst others, revealed that measurements of salinity can now be made to an accuracy of some 0·003‰, but on account of the slight errors introduced in interpolating values for calibration and drawing curves a routine accuracy of 0·01‰ has been accepted.

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*These samples were obtained from a Reference Station at Lat. 41° S, Long. 178° E, which has been sampled at six-monthly intervals for temperature, salinity, and C^{14} activity.

ACKNOWLEDGMENTS

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A NOTE ON ERRORS IN DEPTH CALCULATED FROM UNPROTECTED DEEP-SEA REVERSING THERMOMETER READINGS

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Abstract

Errors in depth, as computed from deep-sea thermometer observations, are investigated and their magnitudes given. It is shown that aggregate errors can be reduced significantly by applying "transfer corrections" obtained from observations on an occasion when the hydrological wire was straight. These corrections, when added to L−D values or stem-corrections, are of considerable value. The remaining inaccuracies are mainly due to reading errors. The attainable accuracy is shown to be of the order of 0–4 m, and consequently unprotected thermometers can be considered satisfactory depth gauges for general hydrological investigations.

INTRODUCTION

When paired protected and unprotected thermometers are lowered into the sea on a hydrological cast, the pressure of the sea water at depth causes a higher temperature reading on the unprotected thermometer. Using the correct reading of the protected thermometer, the depth of observation can be computed from the difference by the formula of Wüst (1933):

$D = (T_u - T_p)/\rho_m \cdot Q$, where D = the depth of observation in m
T_u = the unprotected thermometer reading in °C
T_p = the protected thermometer reading in °C
ρ_m = the average density of the water-column between the ocean surface and the thermometers in g/cm^3
Q = the pressure coefficient of the unprotected thermometer in °C per 100g/cm^2 of pressure.

This depth cannot, in general, be ascertained from the amount of wire paid out alone, because of the deflecting action on the wire of currents and the drift-movements of the ship.

Teramoto (1958) investigated errors in depth determination by this formula and found that, if Q decreased with depth, a systematic error was introduced of at most -2 m, while variations in ρ_m in any limited area could not account for more than $\pm 0{\cdot}2$ m. $T_u - T_p$ was thought to contain no systematic error and the remaining discrepancies were accepted as accidental.

$T_u - T_p$, however, can have a systematic error for an individual pair of thermometers since glass, being a semi-liquid, does not follow Hooke's elastic law accurately, but may be both permanently and temporarily distorted by stress. Generalised observations on the behaviour of unprotected thermometers indicate that: (1) thermometers tend to develop an increasing positive error of depth with time and/or use; and (2) observations at shallow depths suffer most from inaccuracy. We will examine their behaviour under stress with the aid of a rheological model.

BEHAVIOUR OF GLASS UNDER STRESS

When glass is subjected to stress, three properties (Jones, 1956) become evident:

(a) an instantaneous (Hookean) elastic strain,

(b) a viscous (Newtonian) flow which proceeds at a constant rate and is not recovered on removal of the stress, and

(c) a "delayed" elastic (Kelvinian) deformation whose rate decreases exponentially with time of loading and which is exponentially recovered on removal of the stress.

Using the symbols of springs and dashpots (Reiner, 1949, 1959) a rheological model can be built up. In its construction it must be remembered that glass, as an undercooled liquid, may behave as both a liquid and a solid at the same time.

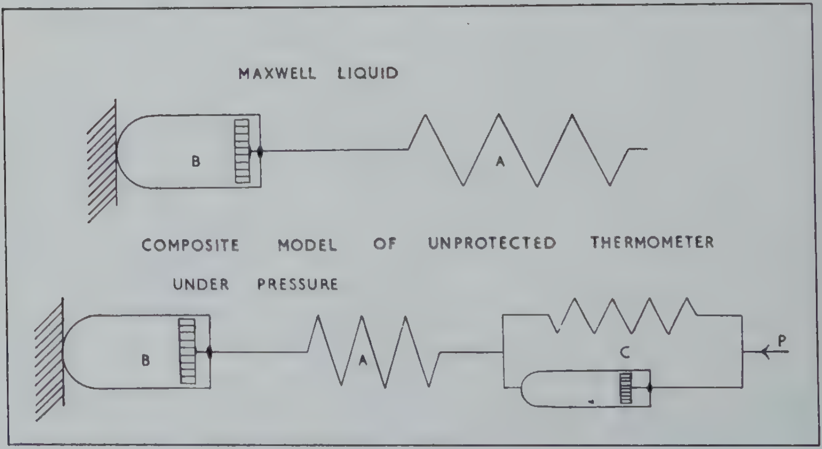

FIG. 1—Rheological models.

A spring (A) in Fig. 1 represents the Hookean properties of (a) above. To allow for property (b), a dashpot (B), also known as a "Newton Body", is connected in series with the spring.

The model now demonstrates the properties of what is known as the "Maxwell liquid". Should the Hooke spring be rather weak and the dashpot oil very viscous, then if the spring is pushed in and released rapidly, the plunger will hardly have moved at all. The body has the appearance of an elastic solid. But when the spring is left in the state of compression the plunger will move. Depending on the viscosity of the oil in dashpot **B** (η_n) it may be hours, weeks, or centuries before the fluid properties become apparent.

Finally, to allow for property (c), a "Kelvin Body", consisting of a spring and a dashpot in parallel (**C**), is fitted in series with the "Maxwell liquid". This dashpot contains oil of viscosity η_k ($\eta_k < \eta_n$) and serves to delay the movement of its parallel spring. Otherwise its ultimate behaviour is Hookean. When the complete model is exposed to stress, both springs will contract; **A** immediately, **C** slowly, until the plunger of its parallel dashpot has "hit the bottom", when it will move no further. Meanwhile the dashpot **B** has started to move and will continue to do so until the stress is removed, or (in the practical application) until so much time has passed that the mercury in the thermometer fully fills the stem.

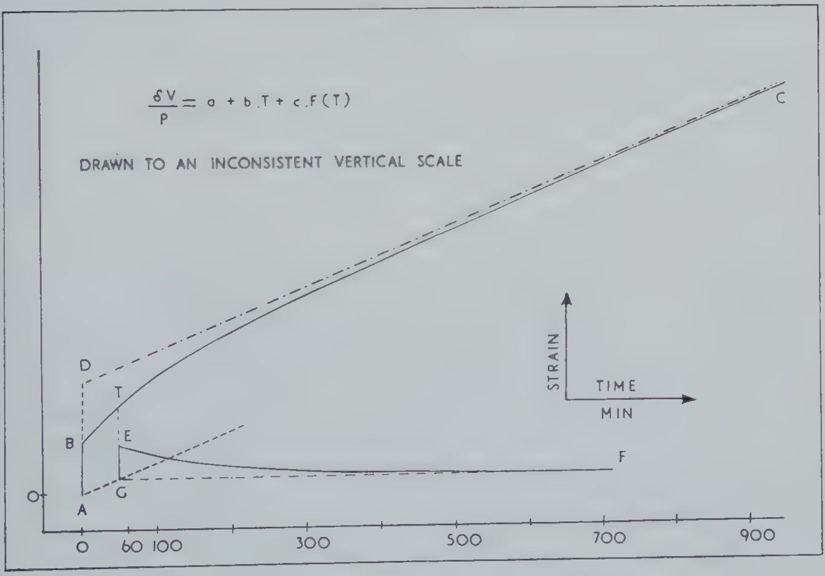

FIG. 2—Graph of compression and decompression.

Fig. 2 illustrates the compression of the model with time. The instantaneous Hookean compression is represented by the movement along **AB**. From then onwards the curve **BC**, which has the line **DC** as its asymptote, represents the delayed compression. **AD** is the maximum obtainable compression under the available stress as resulting from properties (a) and (b).

When the stress is removed prior to having fully developed its strain, as is always the case in practice, at a time *T*, then the decompression follows the curve **EF**. The slope of **AG** represents the constant rate of viscous flow.

MAGNITUDES OF ERRORS

To illustrate the approximate magnitudes of the errors involved through the peculiar behaviour of glass under stress we will represent the compression by the equation:

$$\delta V/P = a + bT + cF(T) \qquad \text{(1)}$$

V is the total strain, caused by the stress P; $a = 1/\gamma$ where γ is the modulus of rigidity of the glass.

The factor b is proportional to $1/\eta_n$, where η_n is of the order of 10^{20} at sea temperatures. Jones (1956) reports that at the maximum stress that can be borne the fractional decrease would not exceed $3 \cdot 10^{-5}$ volume units per year at ordinary temperatures. With a bulb volume of $1 \mathrm{cm}^3$ and a cross-sectional area of the capillary of $34 \cdot 10^{-5} \mathrm{cm}^2$, this would amount to a rise of 0·2°C, or 20 m of equivalent depth per year, which is some 0·002 m per hour of maximum-depth immersion. This error will thus accumulate and is of approximately the same magnitude as the well known "secular" rise of the zero point of all thermometers through "settling" of the glass. Herdman and Pemberton (1958) have determined this "secular" rise for deep-sea thermometers and found it to be some hundredths of a degree in the early years of life.

The factor $cF(T)$ is more complex. For glass it takes the form (Jones, 1956):

$$F(T) = 1 - e^{-\sqrt{(T\gamma/\eta_k)}} \qquad \text{(2)}$$

(e = base of natural logarithms).

The value of η_k/γ is called the retardation time. Thus for $T < \eta_k/\gamma$ the development of the delayed strain is more rapid, and for $T > \eta_k/\gamma$ it is slower than accounted for by our model. A complex model, having infinite numbers of Kelvin bodies in parallel with values of η_k/γ continuously distributed from zero to infinity, instead of a single Kelvin body, would be an ideal representation. The magnitude of the delayed strain as related to a "spread" of retardation times of this complex model is represented in the factor c, however.

At room temperature the value of the ratio c/a in equation (1) above is only of the order of 1–2% (Jones, 1956). The thermometers were tested and certificated after manufacture, which involved reading of the zero point after one hour of imersion under a pressure of some 1·6 tons per square inch, and therefore the error in depth, caused by the elastic effect, would be negative if the immersion in the sea was less than one hour, positive if more than one hour. Because the deep thermometers are placed on the wire first, as the wire is paid out, and are therefore immersed for a longer time, they would suffer the greatest error since a deep hydrological cast is not usually completed within an hour. Because the difference between one hour and the actual time of immersion prior to reversing is small, it is clear that only a fraction of the value of c/a would be realised, with consequent negligible effects on a later cast. There exists, amongst some oceanographers, the belief that when a thermometer has been at a great depth, immediately prior to a shallow cast, and the "Kelvin body" has thus not been given enough time to expand fully, then the remaining compression would cause a high reading on the shallow cast. No quantitative basis appears to exist for this assumption.

OTHER ERRORS

The original calibration certificates issued with the thermometers* used in the field checks described later state that the maximum accuracy (error of setting) is 0·02°c. The rulings on the stem are to 0·01°c on the unprotected thermometer and to 0·01° or 0·02° on the protected thermometer. Accordingly, the maximum errors of reading and setting combined in the difference value $T_u - T_p$ could be as high as 0·06°c, or 6 m of equivalent depth. Teramoto (1958), however, found a probable error of 0·01°c for each individual reading and therefore this figure reduces to some ± 2 m. One improvement would be to photograph the readings with a specially-set-up, illuminated, antiparallax camera. This would be very difficult for the unprotected thermometer, which usually has drops of water attached to the inside of its jacket. The method would also require a special system of marking serial numbers in the field of view of the camera.

DISCUSSION

The following errors in T_u–T_p can be stated to exist:

error of setting:	up to ±4 m
error of reading:	up to ±4 m
errors due to viscous flow and secular rise:	up to some +10 m
error due to delayed elasticity from previous cast:	negligible
errors in ρ_m and Q:	±0·2 and −2 m respectively.

Frequent zero-point determinations would eliminate errors due to viscous flow and secular rise, but at ordinary pressure such a determination may be very inaccurate. At shallow depth unprotected thermometers are not often used, because the deflecting action of the currents is small and depths can be worked out easily from wire angle and wire length paid out. It will be clear that all errors grow proportionally larger as depth becomes shallower. Towards the ocean surface T_u-T_p values become small and the errors may become greater in magnitude than the values of T_u–T_p themselves. This is why one can obtain such unrewarding results from zero-point determinations at normal pressures. Ten thermometers were repeatedly tested in a perforated perspex cylinder with small ice cubes both inside and outside the cylinder. Table 1 shows the results obtained. The only conclusion that could be reached was that there was a general rise in zero points equivalent to 0–10 m, but there were also some negative values and repeated tests gave inconsistent results.

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*Negretti and Zambra, type M2185A, range: −2 to 30°c, selected for previously consistent performance.

Table 1—Rise of Zero Points with Respect to Values Given by Certificates (in °c)

Thermometer	Result from Table 2	Successive Zero Points at Ordinary Pressure		
		1	2	3
9683	0·08	0·01	0·08	0·02
9684	0·01	0·00	0·04	0·02
9691	–	0·00	0·01	−0·01
12095	–	0·00	0·02	–
12101	–	0·00	0·04	–
12265	–	0·01	0·02	0·04
12275	0·09	0·00	−0·05	0·02
12497	0·05	0·10	0·07	0·08
12506	0·04	0·10	0·10	0·10
13401	–	0·00	0·03	−0·01

To reduce errors, a transfer method can be used. It is necessary to perform a perfectly straight cast. This opportunity usually presents itself from time to time. Deviations of computed depth from the wire depth are worked out and applied as corrections on the other casts. This procedure eliminates all zero-point errors, errors in ρ_m and Q, and to some extent errors of setting and reading for any pair of thermometers used.

Application to Field Results

Observations obtained during the cruise of H.M.N.Z.S. *Kaniere* in November 1958 commenced with a cast to 450 m at N.Z.O.I. Station B 97, which was located on the Campbell Plateau north of the Auckland Islands, in a region where strong shallow currents are not expected. The density was found to be constant with depth within 0·3% and no thermocline was located. The computed depths were in excess of the wire depths. Since this is physically impossible—it implies that the wire was stretched—it could be safely assumed that the cast was in fact almost perfectly straight. This cast allowed errors to be approximated, and subsequent casts were corrected accordingly. Table 2 shows initial corrections obtained and subsequent behaviour of ten of the thermometers. Fig. 3 shows a graph of wire length minus computed depth (L−D, *see* Lafond, 1951) against wirelength for N.Z.O.I. Station B 106. The maximum error on this cast due to disregarding the transfer correction would not amount to more than 5 m. The average errors, for the ten thermometers and the ten stations considered in Table 2, however, show that a reduction from 5·6 m to 0·1 m in L–D discrepancies has been obtained. This means that practically all "accidental" errors, even on shallow casts, present in thermometric depth calculations can be removed by using the straight-cast transfer method. The thermometric error of ±0·02°c would, of course, average to zero for a large number of thermometers. The majority of variations in the subsequent behaviour section of Table 2 are within the range 0–4 m. Several thermometers were immersed for one and a half hours at 2000 m and continuously reversed and read upon retrieving. No noticeable elastic after effects were registered, but the observations were subject to the inaccuracy of all observations at normal pressure to which we have already referred.

TABLE 2—Thermometer Corrections and Remaining Errors

Correction in m Found at Stn. B97 and Applied to (L–D) at Other Stns:		Remaining Errors Found *Means Errors > 10 m (Reading Discarded)										Average Error in (L–D)	
Thermometer	Stn											After Correction	Before Correction
	B97	B98	B99	B100	B101	B102	B103	B104	B105	B106	B107		
9683	+8	+1	+1	—	0	+8	—	0	0	0	0	+1·25	−6·75
9684	+1	0	0	—	—	—	0	—	*	−9	0	+1·8	−2·8
9690	+6	−3	*	—	*	—	*	—	0	+3	*	0	−5
12272	*	*	−1	*	—	0	−3	*	—	*	*	—	−1·3
12275	+9	—	+4	−4	—	—	−3	—	+8	*	*	+1·25	−6·25
12277	+4	—	—	—	—	—	−2	−2	0	+2	0	−0·4	−4·4
12497	+5	—	0	−6	—	—	0	—	0	−1	*	−1·4	−6·4
12501	+9	—	−2	−1	—	—	*	—	*	0	*	−1	−10
12506	+4	—	+2	−4	+4	0	0	+4	—	0	0	+0·75	−3·25
16629	+10	+2	+2	—	0	*	—	−1	*	*	*	+0·75	−9·25
								Averages for all thermometers				−0·1	−5·6

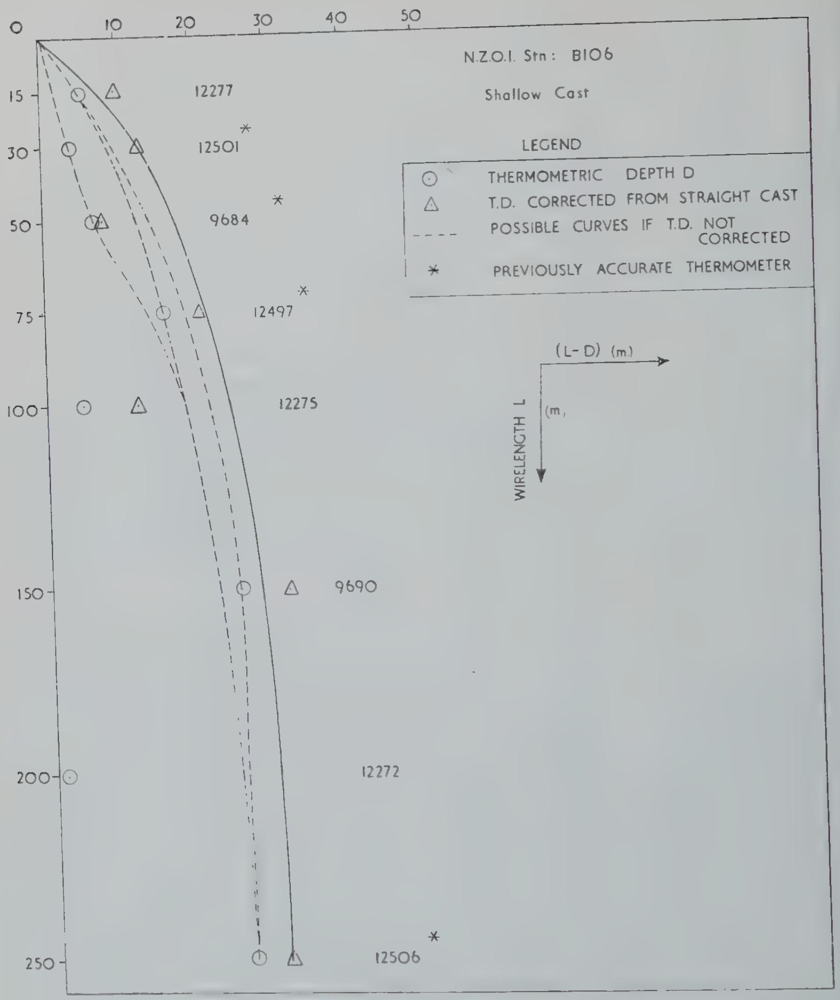

FIG. 3—Graphs of L − D against wire length for Station B106.

CONCLUSION

Using transfer corrections, obtained from a cast where the hydrological wire was straight, unprotected deep-sea thermometers of range −2 to 30°C afforded depth determinations correct to ±4 m. Zero-point determinations at normal pressures are of doubtful use because the combined errors can be as large as the temperature differences being observed. Further improvement would only be possible by reducing reading errors through using photographic recording. T_u–T_p does contain systematic errors, but these are small and the individual determination is difficult.

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MAGNETIC CONCRETE AS AN ARTIFICIAL TRACER MINERAL

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Abstract

Magnetic concrete, composed of crushed ironsand and cement, was used as an artificial tracer mineral in an experiment designed to estimate the sediment-transporting power of the bottom currents in the central part of Cook Strait, New Zealand. The results show that these currents are capable of transporting sand grains at least 1½ mm in diameter.

THE PROBLEM

This paper describes the results of a tracer-mineral experiment recently carried out in the central part of Cook Strait (Fig. 1). The Strait is a zone of strong tidal currents, particularly in the Narrows* between Arapawa Island and Cape Terawhiti (Gilmore, 1960), and these currents have a decisive influence on the nature and distribution of sediment in the area. Relatively fine sediments, consisting of mud and sand in various proportions, are being deposited at the present day near the mouths of the larger rivers flowing into the Strait (Reed and Leopard, 1954), but no such deposition is taking place around the Narrows, where the bottom sediments are much coarser and consist dominantly of gravel and sand. These were evidently laid down during an earlier phase of sedimentation. The absence of more recent sediment may be confidently attributed to tidal currents, as these are strongest in this part of the area, whereas the depth is mostly too great for effective wave action, 75 per cent of the sea floor along the line joining Arapawa Island and Cape Terawhiti lying below 50 fathoms.

The tidal currents around the Narrows are apparently strong enough to transport mud and fine sand and to remove them from the area, but marine growth is abundant on cobbles and is common on pebbles down to about 15 mm in diameter, and it seems clear that the currents are not capable of transporting the cobbles and larger pebbles. The maximum particle size that can be transported by these currents thus lies somewhere in the range 0·1 to 15 mm. The experiment described in this account was designed to provide further information regarding the maximum transportable size.

THE EXPERIMENT

At the outset, it was clear that the transporting power of the tidal currents could be estimated simply by releasing on the sea bed a quantity of identifiable sediment with a suitable grain size, and returning later to sample in the surrounding area to find out whether any of the material

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*An obvious name, here formally applied to this part of the Strait.

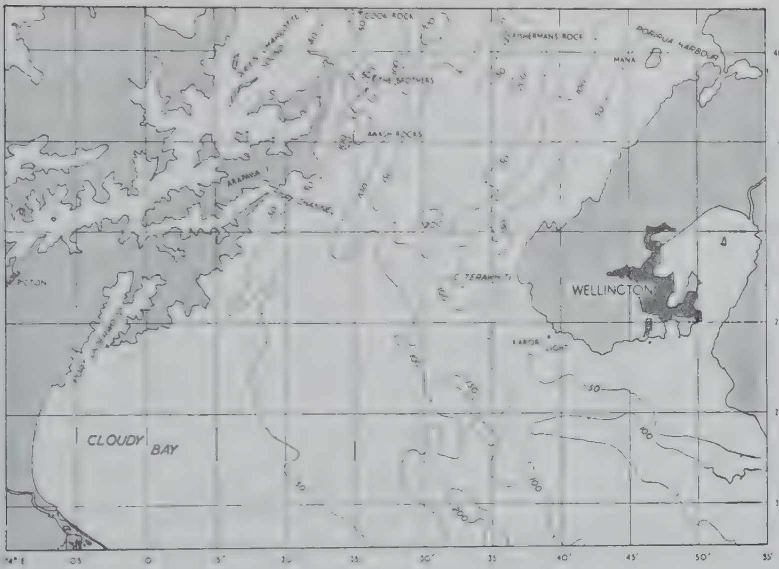

FIG. 1—The Narrows, Cook Strait. Isobaths at 50-fathom intervals.

had been moved from its original position. A number of factors, however, had to be taken into account with regard to the preparation of the tracer sediment. The material would have to be easy to distinguish from the normal mineral grains of the area and identifiable in concentrations as low as 1 in 10^8. It would also have to be sufficiently resistant to withstand abrasion by the hard natural sand grains, most of which consist of quartz or quartzose greywacke. Finally, it must be reasonably cheap and easily procurable in suitable grain sizes.

Several possible materials were considered, each based on a particular physical property which would be used to identify the tracer sand. Although radioactive tracer sediments have been successfully used for experiments in several other localities, this method was rejected in the present case. To produce detectable results at the required dilutions, the original sample would have to be highly radioactive, and would thus be dangerous to use unless very extensive (and expensive) precautions were taken. Furthermore, it would be difficult to identify the individual grains of tracer mineral by radioactivity alone. Materials showing fluorescence under ultraviolet light were also considered, but were again rejected as being too difficult to obtain or too expensive. A magnetic material, on the other hand, appeared to be suitable from every point of view. It would be completely safe, easy to separate magnetically, and large quantities of source material were available in the form of natural ironsand, containing a high proportion of magnetite, on the west coast beaches of the North Island.

Owing to the occurrence of a small proportion of natural ironsand in the sediments of Cook Strait, it was not possible to use the west coast ironsand directly, and it was therefore decided to powder the natural ironsand and incorporate it with cement in a concrete mix, the resulting concrete being subsequently crushed to the required grain size. It was calculated that about half a cubic metre of concrete would be necessary to produce satisfactory results, and accordingly 28 cwt of concentrated ironsand was obtained from a locality on the coast near the mouth of the Patea River. The ironsand contained about 80% of titaniferous magnetite, with a mean grain diameter of about 0·15 mm, the remainder being augite, hornblende, and plagioclase with a mean grain diameter of about 0·3 mm. This was mixed with water to form a slurry, and ground in a continuous-feed ball-mill until the average grain size was reduced to about 0·04 mm. The material then consisted of small crushed grains accompanied by a minor proportion of much larger grains which were derived from the original ironsand and happened to escape crushing. The slurry was then mixed with cement in the proportion of 3 parts by weight ironsand to 1 part cement, and allowed to set for several days: this produced a concrete with a satisfactory mechanical strength, although the material was somewhat weaker than ordinary concrete made with quartzose sand. The magnetic concrete (38 cwt) was then broken up and crushed in a roller mill, with a gap of about 3 mm between the rollers.

A locality (station A430, 41° 19·75′ S., 174° 30·60′ E., ± 0·1 mile) 6½ miles W by N of Karori Light was selected as the place for releasing the magnetic concrete (Fig. 2). This locality lies well within the zone of coarse sediment in the Narrows, and is situated near the axis of the submarine channel defined by the 100-fathom isobaths. A shallow-silled 150-fathom basin lies a few miles to the south, and a 200-fathom basin to the north, and it was considered that the artificial sediment would probably move parallel to the channel and might tend to collect in the basins. Moreover, the locality lies well below the level of effective wave action, so that any effect observed must be due to tidal or other currents.

On the evening of 1 October 1958, the magnetic concrete was released on the sea bed at the above locality, the following procedure being used. Steel bridles were welded to both ends of a 44-gallon oil-drum with the upper end cut away. The upper bridle was then placed in a counterweight release gear normally used for a piston corer, and the lower bridle was connected to the top of the release gear by a slack loop of wire. A suitable weight on a rope about 10 ft in length was attached to the end of the counterpoise lever. The drum was then about one-third filled with magnetic concrete and the rig lowered to the sea bed. As soon as the counterweight grounded, the top of the drum was automatically released and it turned upside down, leaving the concrete on the bottom.

Seven separate loads, covering a period of 4½ hours (18.15 to 22.45), were necessary to release all the concrete, and the positions of these varied slightly, as it was difficult to keep the ship on station in the tidal stream. However, the maximum scatter was only 1/5 mile, which did not affect the outcome of the experiment.

Since the tidal stream flows backwards and forwards through the Strait twice in 24 hours, it was estimated that if a positive result was going to be obtained at all, it could be obtained within a few days of releasing the material. Accordingly, samples (a) to (i) were taken 82–89 hours after

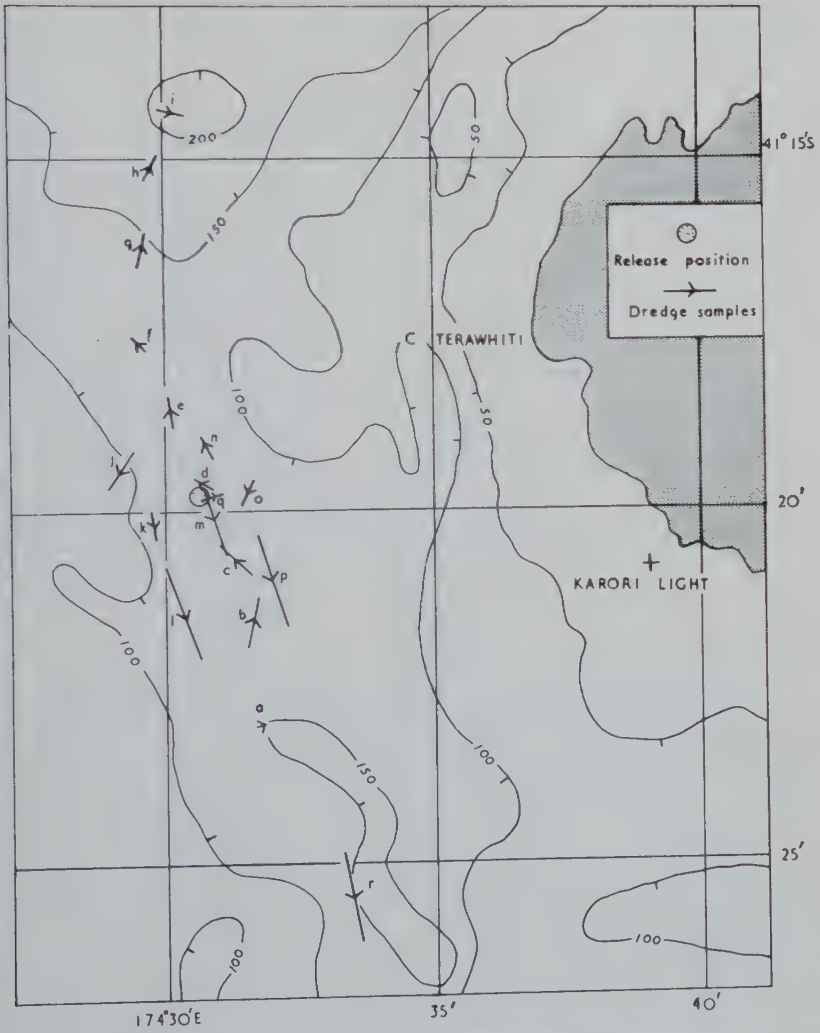

FIG. 2—The release position (stippled) and the subsequent sample positions (lettered arrows). The beginning and end of each arrow show the approximate positions of the ship at the beginning and end of each dredge haul. Isobaths at 50-fathom intervals.

the release had been completed, and samples (j) to (r) on the following day, 111½–118½ hours after the release (Fig. 2 and Table 1). The majority of samples were located along a line running parallel to the channel and extending from five miles south to five miles north of the release position, the remainder being concentrated in the neighbourhood of the release position itself. The samples were collected with a flat box-dredge measuring 6 in. × 30 in. (aperture) × 30 in. (depth), and designed to scrape a thin layer off the top of the sediment rather than to penetrate deeply into it.

TABLE 1—Dredge Sample Positions (Stations A444a to A444r)

Sample	Dredge Lowered	Dredge Raised
a.	41° 23·05′ S. 174° 31·70′ E.	41° 23·00′ S. 174° 31·80′ E.
b.	41° 21·90′ S. 174° 31·50′ E.	41° 21·20′ S. 174° 31·70′ E.
c.	41° 20·90′ S. 174° 31·60′ E.	41° 20·50′ S. 174° 31·00′ E.
d.	41° 19·70′ S. 174° 30·90′ E.	41° 19·50′ S. 174° 30·50′ E.
e.	41° 18·80′ S. 174° 30·15′ E.	41° 18·35′ S. 174° 30·05′ E.
f.	41° 17·70′ S. 174° 29·65′ E.	41° 17·55′ S. 174° 29·40′ E.
g.	41° 16·50′ S. 174° 29·55′ E.	41° 16·10′ S. 174° 29·65′ E.
h.	41° 15·25′ S. 174° 29·70′ E.	41° 15·00′ S. 174° 29·85′ E.
i.	41° 14·30′ S. 174° 29·95′ E.	41° 14·40′ S. 174° 30·45′ E.
j.	41° 19·15′ S. 174° 29·40′ E.	41° 19·65′ S. 174° 28·95′ E.
k.	41° 20·00′ S. 174° 29·75′ E.	41° 20·35′ S. 174° 29·80′ E.
l.	41° 20·80′ S. 174° 30·00′ E.	41° 22·10′ S. 174° 30·60′ E.
m.	41° 19·70′ S. 174° 30·70′ E.	41° 20·65′ S. 174° 31·15′ E.
n	41° 19·20′ S. 174° 30·80′ E.	41° 18·90′ S. 174° 30·60′ E.
o.	41° 19·55′ S. 174° 31·65′ E.	41° 19·95′ S. 174° 31·45′ E.
p.	41° 20·30′ S. 174° 31·70′ E.	41° 21·65′ S. 174° 32·25′ E.
q.	41° 19·85′ S. 174° 30·60 E.	41° 19·75′ S. 174° 31·05′ E.
r.	41° 24·90′ S. 174° 33·30′ E.	41° 26·05′ S. 174° 33·60′ E.

The samples consisted of gravel accompanied by variable but usually abundant quantities of sand, the average volume being about 1½ cubic feet (half the volume of the dredge). The magnetic fraction was separated in the laboratory in a magnetic flume (Fig. 3), consisting of a galvanised iron tray narrowing down at one end into a small brass channel running between the poles of a large permanent magnet. To remove the gravel fraction, each sample was placed in a large sieve with ⅛ in. mesh fitting on top of the tray, and the sand was washed through the sieve and down the flume by means of a hose fitted with an adjustable jet nozzle. The magnetic fraction adhered to the sides of the brass channel, which were recessed with drilled holes to prevent any magnetic material being brushed off or washed away: the remaining mixture of water and non-magnetic sand flowed into a sink at the lower end of the flume, the sink being fitted with an automatic overflow. The proportion of magnetic material was always low, ranging from about 0·1 down to 0·02 per cent by volume, and although the accumulated magnetic grains tended to clog the channel it was rarely necessary to stop the separation in order to remove the excess material. When all the sand had been washed out of the gravel, the magnetic fraction in the flume was removed, and the sand in the sink (which had passed through the flume) was washed through again. The quantity recovered during this second run was always far less than before, the original recovery for every sample being at least 95 per cent effective.

RESULTS

The magnetic fractions were found to consist mainly of natural ironsand, accompanied by small fragments of magnetite-rich sedimentary, metamorphic, and volcanic rocks, magnetic rust and cinder fragments derived from ships, and rare grains of magnetic concrete. Each sample was dispersed under water in a 4 in. petrie dish, and examined by reflected light under a binocular microscope. The magnetic concrete proved easy to identify visually, and a few grains at least were found in every sample. The smallest number (3) occurred in (b) and (m), and the largest number (37) in (j). Outlines of the recovered grains, drawn from photomicrographs, are shown in Fig. 4 and two of the actual photomicrographs are reproduced in Fig. 5.

The mean diameter of the largest recovered grains ranges up to about 1½ mm. This shows that the currents near the bottom are capable of transporting magnetic concrete grains up to 1½ mm in diameter, and ordinary sand grains slightly larger than this, allowing for the greater density of the concrete (about 4) as compared with that of normal sand grains (about 2·7). It is probable, however, that the maximum transportable size is not greatly in excess of 1½ mm. Twenty to thirty per cent by volume of the crushed concrete was made up of fragments over 2 mm in diameter, but none of these larger fragments was found in the samples; this indicates that the bottom currents were not powerful enough to transport grains of this size.

The grains cannot have travelled directly to the recovery position, but must have followed irregular and frequently oscillating paths. It is therefore not possible to calculate their true rate of transport while in motion. The maximum net rate of movement that can actually be proved

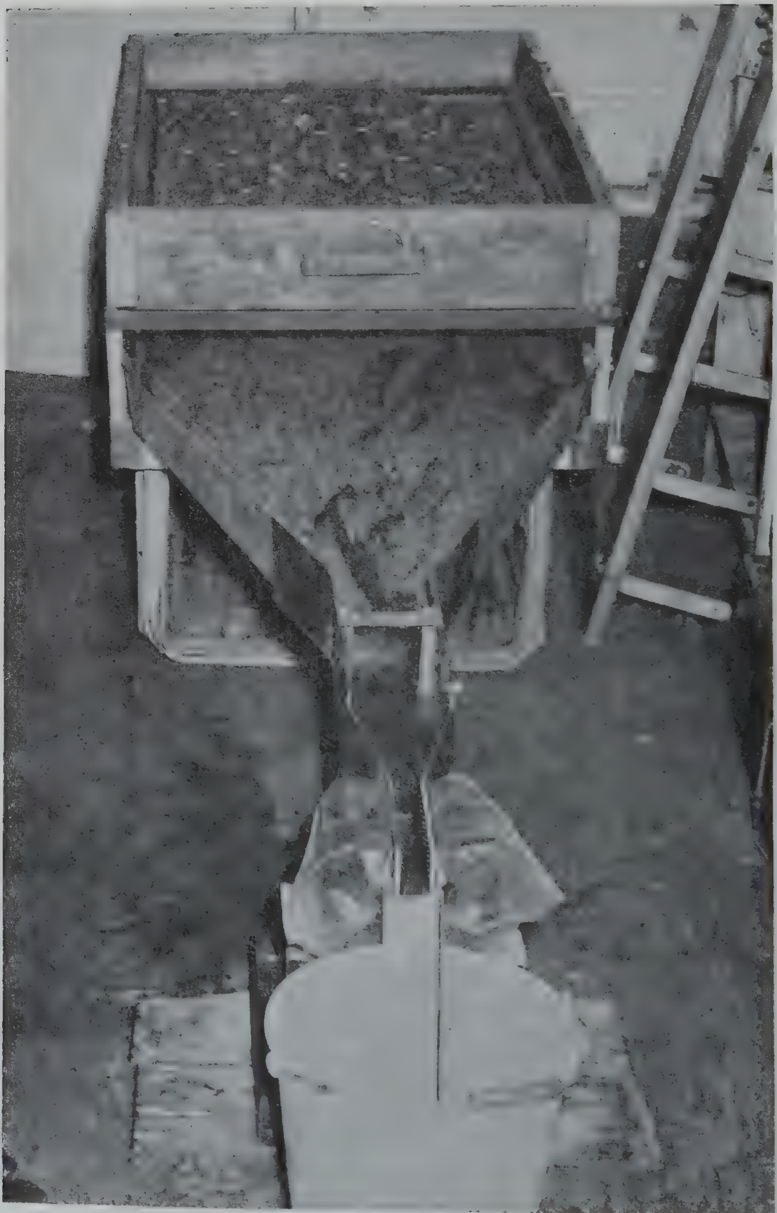

FIG. 3—The magnetic flume. The permanent magnet is enclosed in a plastic cover to prevent contamination. The brass channel between the poles of the magnet is 1 in. wide and 5 in. long. The sieve above the galvanised iron tray is 2 ft wide and 3 ft long.

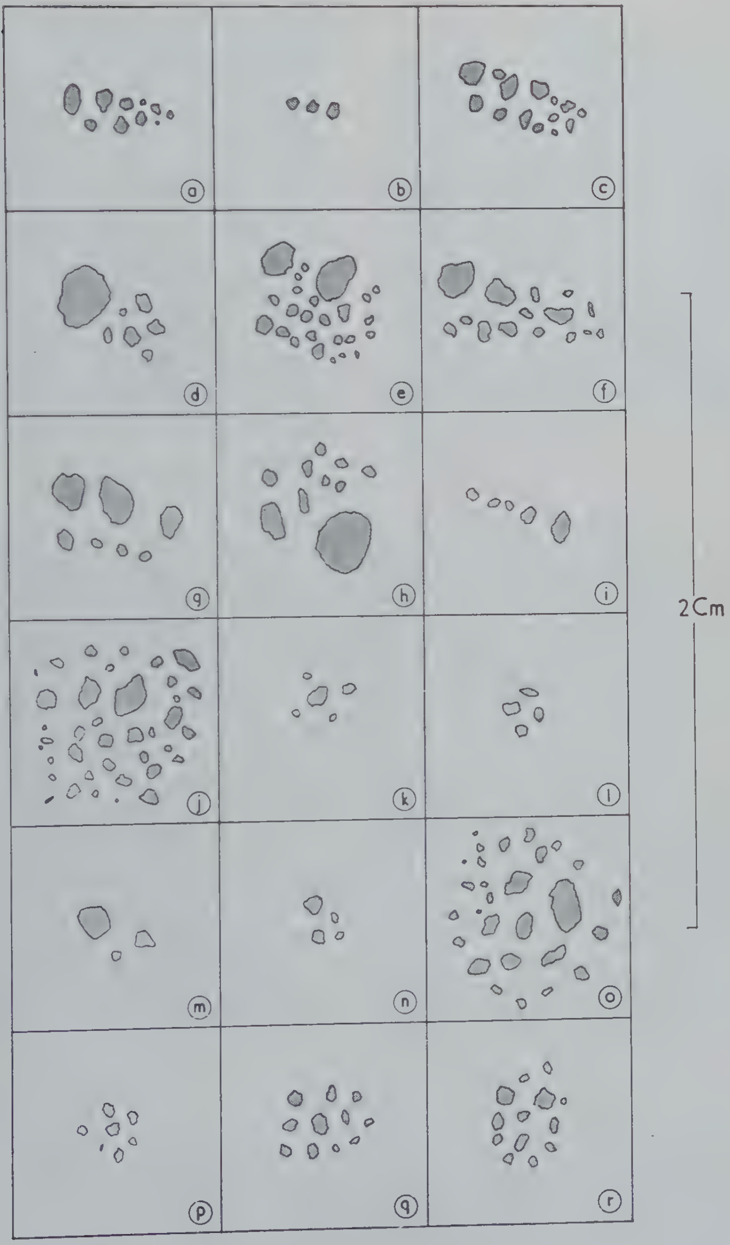

FIG. 4—Outlines of the recovered magnetic concrete grains, drawn from photomicrographs.

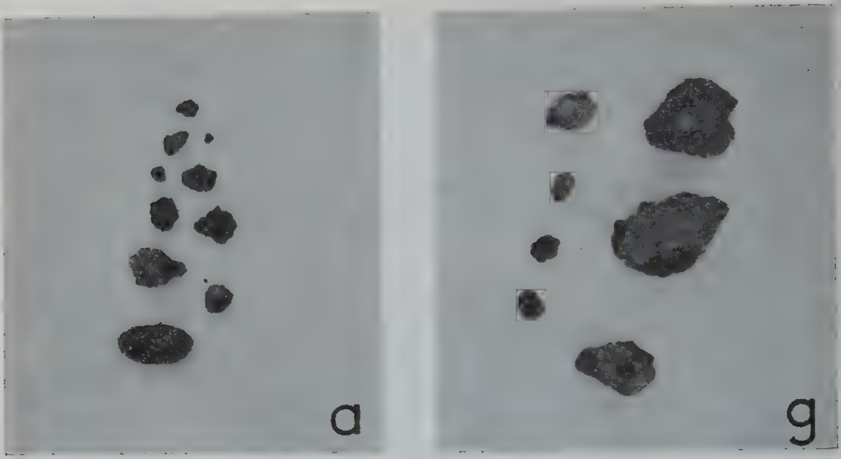

FIG. 5—Photomicrographs of magnetic concrete grains recovered in samples (a) and (g). For scale compare Fig. 4.

in terms of time and distance travelled is 1⅓ miles per day, for sample (i), but the total movement during the time was probably much greater than this, as the reversing tidal currents would tend to sweep a given particle backwards and forwards over the same area, and the net movement would be small relative to the total distance travelled.

The amount of material recovered also indicates that much of the magnetic concrete must have travelled considerably further than was proved directly by sampling. The average volume of concrete recovered at a single station was about 1½ mm^3. The total volume of the original material was about ½ $metre^3$, but the volume consisting of grains 1½ mm or less in width would be less than this, say ⅓ $metre^3$ ($= \frac{1}{3} \times 10^9$ mm^3). Assuming that each sample represents approximately 1 $metre^2$ of sea bed, the total area which could theoretically have been covered by the concrete at a concentration of 1½ mm^3 per $metre^2$ would be 220 km^2 (about 85 square miles). The effective area sampled by dredging was only one-sixth of this, and so at the time of sampling a large proportion of the concrete had probably travelled up to $\sqrt{6}$ times the distance of the outer samples from the release position, and perhaps even further than this.

DISCUSSION

The results of the magnetic concrete experiment agree reasonably well with experimental data on the transporting power of currents. Nevin (1946), using a traction tube, showed that a minimum velocity of 40 cm per second was necessary to transport grains with a diameter of 1 mm, and Gilmour (1960, pp. 424–30) has made measurements which show that normal bottom currents in the Cook Strait Narrows reach 0·8 to 1·0 knot (40–50 cm per sec).

The principle of magnetic separation could well be used for similar experiments in other areas, although magnetic concrete as made for the Cook Strait experiment would not always be the most suitable material. Artificial magnetic slag might be a good substitute for ironsand. Since the grain size of the magnetic ingredient must always be considerably smaller than that of the eventual tracer "mineral", ball-milling would not be adequate if it were desired to use the tracer in the form of fine sand or silt, and some other process such as micronisation in an air-blast would have to be used. Again, the strength provided by the concrete medium would not be adequate for some purposes, and it might then be necessary to use magnetic bricks or slag hardened by heat treatment. Radioactivity or rare elements could be incorporated in the tracer mineral to aid identification. A uniform, mechanically resistant material, which can be readily identified and can be separated magnetically in very low concentrations, fulfils the basic requirements of an effective tracer mineral.

ACKNOWLEDGMENTS

In conclusion, the writer wishes to express his best thanks to the following members and former members of the New Zealand D.S.I.R. who rendered valuable assistance during the preparation of the experiment: Messrs R. A. Kennerly, D. S. Nicholson, and D. A. St John, Dominion Laboratory; Mrs J. C. Mentha (formerly Miss I. M. Todd, Institute of Nuclear Sciences); and Messrs S. Kustanowich, J. C. McDougall, and N. M. Ridgway, N. Z. Oceanographic Institute. In addition, thanks are due to the New Zealand Naval Board for their assistance in making available R.N.Z.F.A. *Tui*, from which vessel the experiment was carried out.

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QUATERNARY SURFACES AND SEDIMENTS AT WAIHI BEACH

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Abstract

Levelling, accurate to 1 ft in height, of coastal terraces in the Waihi Beach area, has indicated past sea levels at 6–10 ft (Waihi Beach Surface, 50–100% preserved), 15–20 ft (Ocean View Surface, about 30% preserved); c.60–70 ft (Athenree Surface, about 15% preserved), and c.110–115 ft (unnamed, preserved solely as accordant ridges) above present sea level. Less accurate levelling by an aneroid barometer showed bench remnants at c.340–390 ft and c.550 ft. (Values indicated by "c." were calculated using the arbitrary assumption that the positions of present and past coastlines were identical). The correlation of levels with those previously established at South Kaipara, is sufficiently good to assume that the Waihi Beach area was relatively stable in at least the late Pleistocene, and to correlate the indicated sea levels with the Post-glacial (6–10 ft), Late Monastirian (15–20 ft), Main Monastirian (c. 60–70 ft), Tyrrhenian (c.110–115 ft), Sicilian (c.340–390 ft), and Calabrian (c. 550 ft) of Europe.

The formations are named after the surfaces below which they accumulated by aggradation, and consist of locally derived clays and sands, with angular pebbles near the hills, rounded pebbles in the river valleys, and dune sands at the coast.

INTRODUCTION

During investigation of the ilmenite-bearing blacksands at Waihi Beach with Messrs H. E. Fyfe and D. S. Nicholson (Nicholson *et al.*, 1958, p. 13), the writers noted that coastal terraces were well exposed there (*see* Bell and Fraser, 1912, p. 50; Morgan, 1924, p. 16). The area, of some 8 square miles, seemed potentially useful for studying the long-range terrace correlations that were initiated by Brothers (1954).

A preliminary investigation of the slopes and heights of the terraces, using an aneroid barometer, failed to provide consistent heights, partly owing to the inaccuracies of some published spot heights. It nevertheless confirmed several distinct terrace levels and led to the detailed levelling of selected traverses.

DETAILED LEVELLING

A base-map was prepared from air photographs, and detailed terrace correlation was attempted with a stereoscope. Three days were subsequently spent in the field, during which the correlations were checked or amended where necessary and seven selected traverses were run using a Cooke, Troughton and Simms S100 survey level and 14 ft staff. High-tide mark (the height of recent debris on the beach) was taken as datum, and was approximately 3 ft above the mean sea level during the time of the field work

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(interpolation from *N.Z. Nautical Almanac* for 1958). All heights were eventually adjusted to mean-sea-level datum, and were finally rounded to the nearest foot. Some traverses were closed circuits, while others were closed to high-tide level at both ends. All such traverses (up to 2¼ miles) closed well within ±1 ft. Traverses with floating ends were tied in by long shots (up to 1 mile) on to recognisable points on other traverses. These also closed to ±1 ft; but in view of the length of shot, the accuracy might be illusory in part. The results are presented as a map (Figs. 2 and 2A) and sections (Fig. 3).

Spot heights were established on adjacent ridges with the use of the level's telescope, compass bearings, and air photographs. These are noted on Fig. 2 as "distant", and have been rounded to the nearest 5 ft.

NOMENCLATURE OF NEW ZEALAND DEPOSITS RESULTING FROM EUSTATIC RISES OF SEA LEVEL

Brothers's (1954, pp. 688–93) observation that terrace levels at South Kaipara (Fig. 1) were similar to those of Europe has led to the adoption of

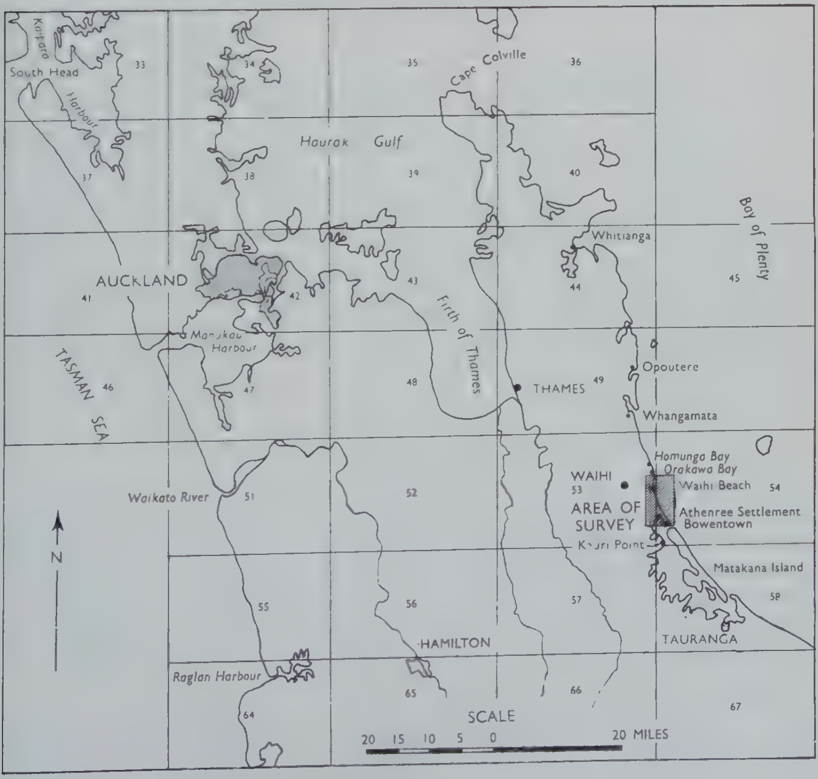

FIG. 1—Locality map.

the European sea-level terminology in the study of New Zealand's eustatic terrace levels. It has proved a useful working framework (e.g., Schofield, 1958; Harrington, 1958; Leamy, 1958; Kear, 1959), and little would be gained by introducing more than the bare minimum of additional terms, at least until firm correlation is established with a South Island glacial chronology (e.g., Gage and Suggate, 1958).

Brothers's (1954) highest level (550 ft) has been correlated by Suggate (1960) with the Calabrian of the European succession. Like the Sicilian (350 ft) level, its acceptance as a consequence of an undoubted sea level at that height should await further confirmatory evidence (e.g., the presence of marine beds at that height, or its recognition in other stable areas). The Milazzian (220–240 ft at South Kaipara) and Tyrrhenian (110–130 ft) need no further comment. Surfaces corresponding to the Main (45–75 ft) and Late (15–25 ft) Monastirian have been recognised elsewhere in New Zealand than at South Kaipara (e.g., at Waihi, *see below*: Porirua, Leamy, 1958; and coastal Otago, Ongley, 1939, pp. 65–6). At Waihi the two levels are broadly similar in preservation, and encourage the double use of the term "Monastirian" in New Zealand. Post-glacial sea-level fluctuations are being actively studied (e.g., Schofield, 1960), and a complex story may emerge. For the purposes of the present paper however, all possible post-glacial high sea levels are treated as one, for which the term "Post-glacial" will be used.

In any specific coastal area, such as Waihi, it is desirable that the detailed local geology should be described in terms of local formations and local terrace surfaces, rather than in terms of European eustatic sea levels. The use of the latter should be restricted to the important task of correlation between areas. In this way, the validity of the morphologic and lithologic descriptions will remain, even if the sea-level correlations are proved subsequently to be incorrect. Not only is it possible that a terrace surface might be correlated with the wrong interglacial sea level, but the differentiation of glacial from interglacial terraces is by no means finally solved throughout New Zealand. In the local nomenclature, new terms will be kept to a minimum if the one name is used for both the terrace surface and the formation that comprises the aggradational sediments below it, and if both are recognised as widely, in a geographic sense, as is prudently possible.

STRATIGRAPHY

The greatest problem in dating terraces is the doubt that often exists as to the precise height of the sea level that is represented. Waihi Beach proved to be no exception. No marine deposits were noted, and the surfaces are assumed to be the result of terrestrial aggradation as a consequence of the rise of sea level. Breaks of slope at the seaward ends of terraces had to be assumed to be the result of erosion, which also would have removed any beach deposits that might have been formed. An idealised diagram, illustrating the sequence of terrace formation is presented as Fig. 4.

Indicated sea level was determined somewhat differently for each particular surface, and for one (Athenree Surface), where no evidence beyond a measured seaward slope was obtained, an arbitrary method of calculation was required. Possibly no numerical value should be deduced in such cases, but it is considered preferable to infer some indicated sea level for every well developed surface so that sequences in different areas can be compared effectively. The uncertainty of such values must of course be indicated (in this paper by "c."). The arbitrary method adopted here assumes that the position in plan of the coastline at the time of formation of the aggradational surface coincided with that of the present day. Whilst there is no strictly logical reason for this assumption, several points support its adoption as an expediency. First, no other reference line would be any more logical; secondly, this reference line is available in all coastal localities; thirdly, coastal benches may be treated similarly to sloping surfaces; fourthly, correlation of Waihi Beach (c.60–70 ft, *see below*) with South Kaipara (45–75 ft, Brothers, 1954), Porirua (51–54 ft, Leamy, 1958), and Otago (50–60 ft, Ongley, 1939) surfaces implies that the values obtained for correlation may well have some practical use; and fifthly, the assumption has been implicit (although seldom stated) in much of the past work that has contributed usefully to our present knowledge (e.g., Morgan, 1924, p. 16, records three "raised beaches" at Waihi Beach, at 12 ft, 20–25 ft, and 40–50 ft above high-water mark, when the only evidence for their being raised beaches is that they are plane and close to the present coast).

The stratigraphic succession is summarised in Table 1 and illustrated diagrammatically in Fig. 4.

TABLE 1—Surfaces and Formations at Waihi Beach

Sea Level (with South Kaipara levels, Brothers, 1954, in parentheses)	Indicated Sea Level	Surface	Sediments or Remarks
Post-glacial (6–12 ft)	6–10 ft	*Waihi Beach*	*Waihi Beach Formation* Sand dunes, swamp, alluvium, and estuarine mud.
Late Monastirian (15–25 ft)	15–20 ft	*Ocean View*	*Ocean View Formation* Fixed clayey sand dunes, weathered brown clays and sands, weathered brown gravels, white clays.
Main Monastirian (45–75 ft)	c.60–70 ft	*Athenree*	*Athenree Formation* Reddish weathered (?ashy) clays overlying white sandy clays with volcanic and carbonaceous fragments.
Tyrrhenian (110–130 ft)	c.110–115 ft	Remnants (unnamed)	Locally derived clayey sands, with angular and rounded pebbles; pumiceous sediments (Tauranga Formation)
and Milazzian (220–240 ft)	—	Absent	
Sicilian (350 ft)	(c.340–390 ft)	At Homunga Bay	Slumped rock benches
Calabrian (550ft)	(c.550 ft)		
Pre-Pleistocene	—	—	Andesites, rhyolites

Values indicated by "c." have been calculated on the assumption that present and past coastlines were identical.

For mapping purposes, the recognition of formations is essential, and they have been given the same type localities as the surfaces. The type exposures, in low road cuttings, are poor, but are normal for the area as a whole.

LEGEND

INDICATED SEA LEVEL	SURFACE		FORMATION	
Post – Glacial	WAIHI BEACH (6–10 ft)	W W W W	WAIHI BEACH FORMATION Alluvial and Estuarine deposits Swamp Sand Dunes	w
Late Monastirian	OCEAN VIEW (15–20 ft)	O O	OCEAN VIEW FORMATION Old reddish clayey sand dunes Gravels in clay matrix White clay	o o o o
Main Monastirian	ATHENREE (?60–?70 ft)	A A A	ATHENREE FORMATION Reddish clays overlying white sandy clay with volcanic rock fragments	a a a a a
Tyrrhenian and older	(?110– ?115 ft)		Locally-derived sediments TAURANGA FORMATION Pumiceous sediments with peat	T T T
Pre-pleistocene			ANDESITE AND RHYOLITE	▤

SURVEYED HEIGHTS (feet) • 72

SURVEYED HEIGHTS (DISTANT) • 69*

PROFILE LINES H — G

BLACKSAND BOREHOLES • A2

LOCALITIES MENTIONED IN TEXT ①

Legend for Figs. 2 and 2A.

Air photographs reproduced in Figs 2 and 2A are published by permission of the N.Z. Department of Lands and Survey.

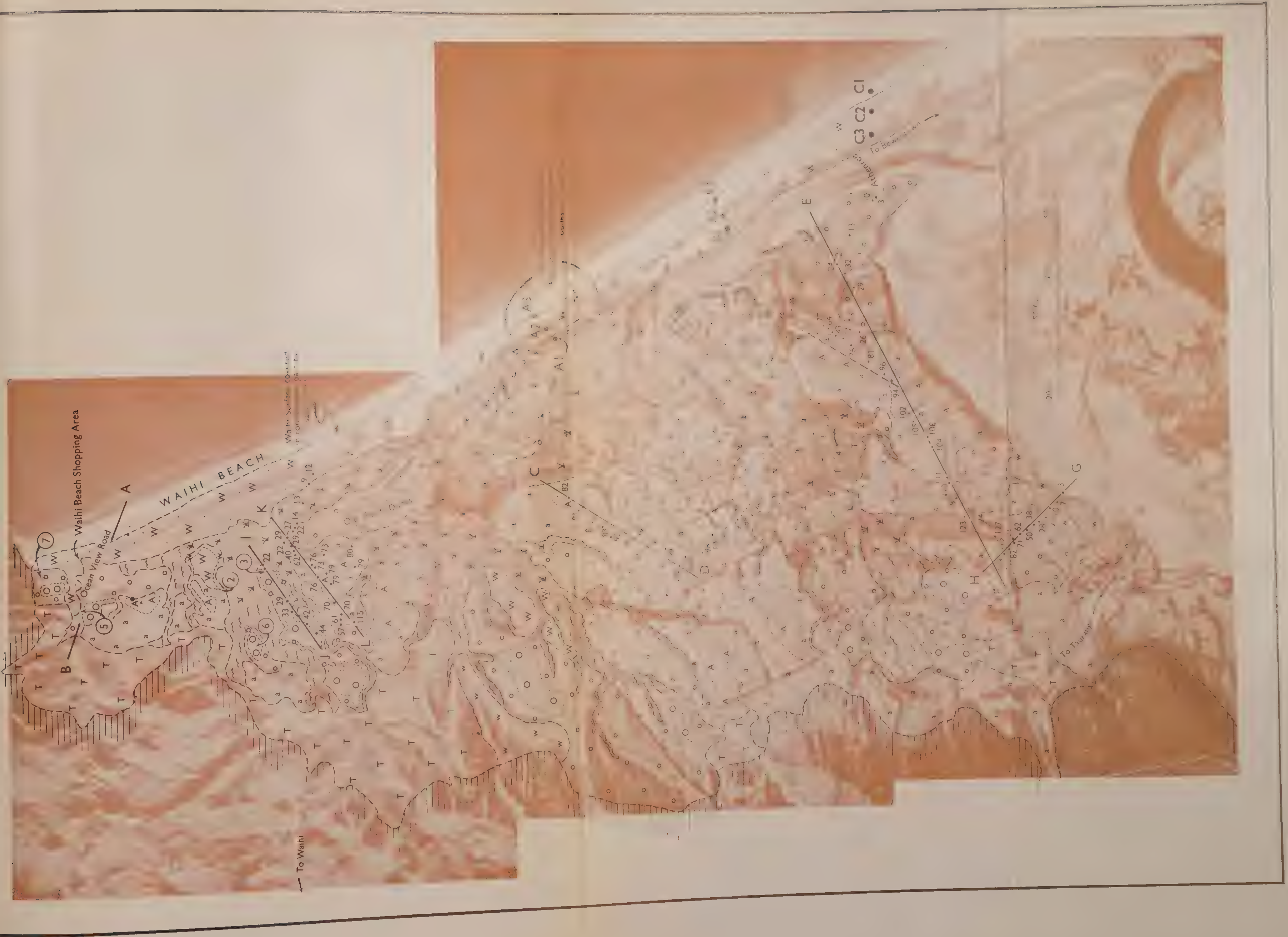

FIG. 2—Quaternary surfaces and sediments, Waihi Beach. For enlargement of northern area, see Fig 2A. For legend see facing page.

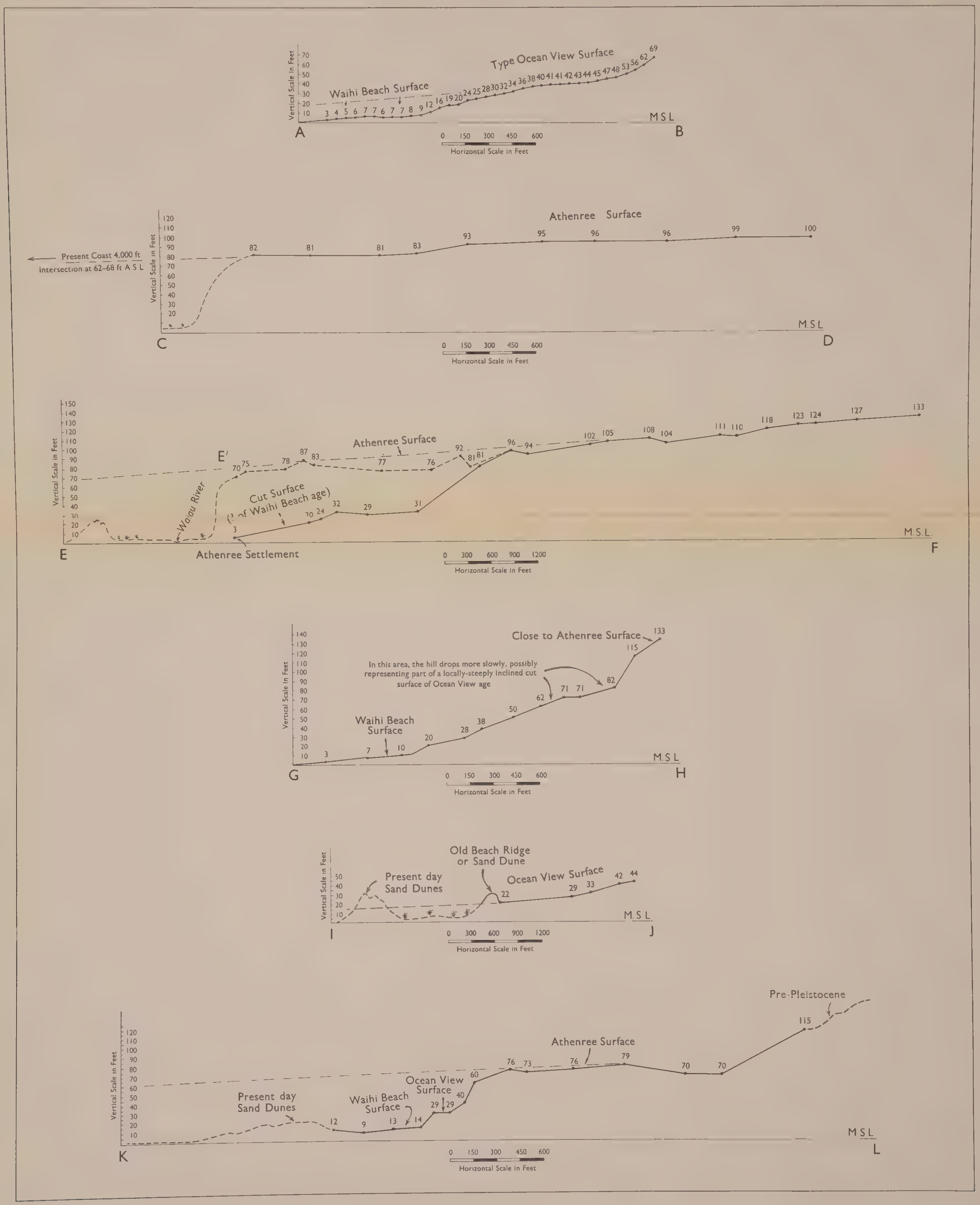

FIG. 3—Profiles of surfaces at Waihi Beach along lines shown in Fig. 2. All vertical scales are exaggerated, AB, CD, GH and KL six times, and EF and IJ twelve times.

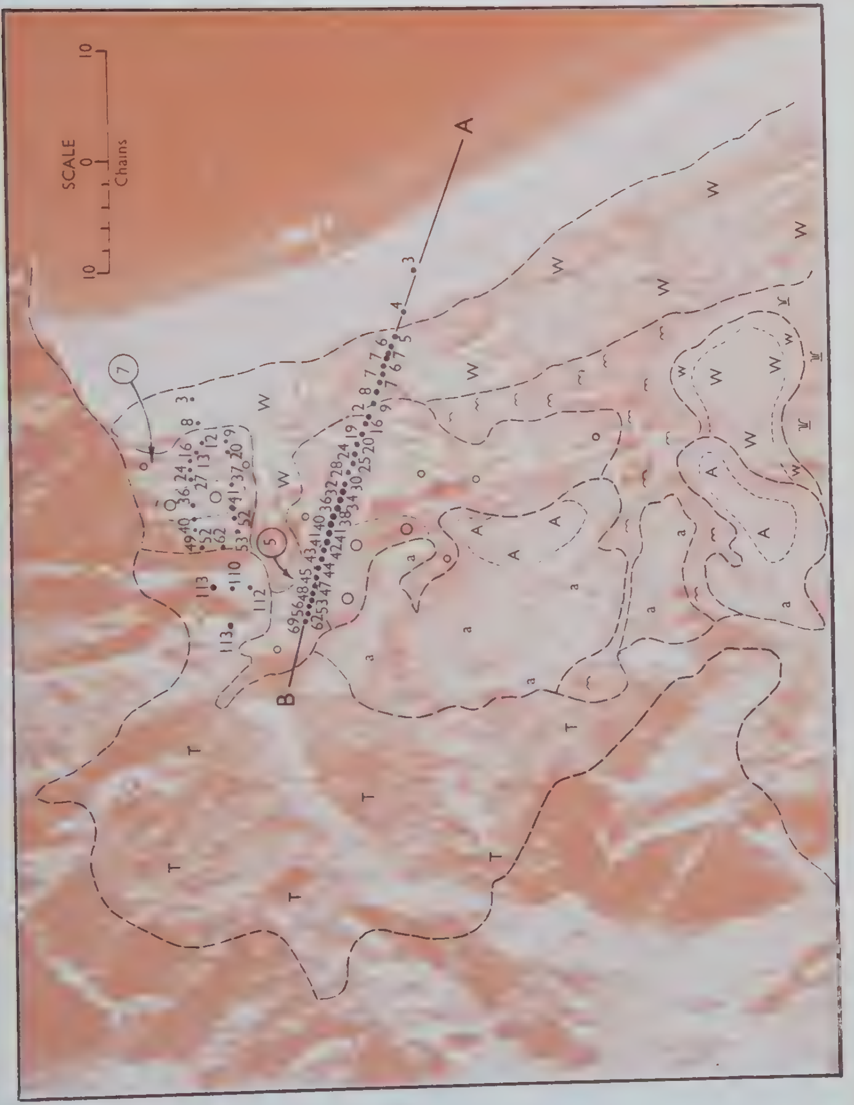

FIG. 2A—Enlargement of northern part of Fig. 2. For legend see page facing Fig. 2.

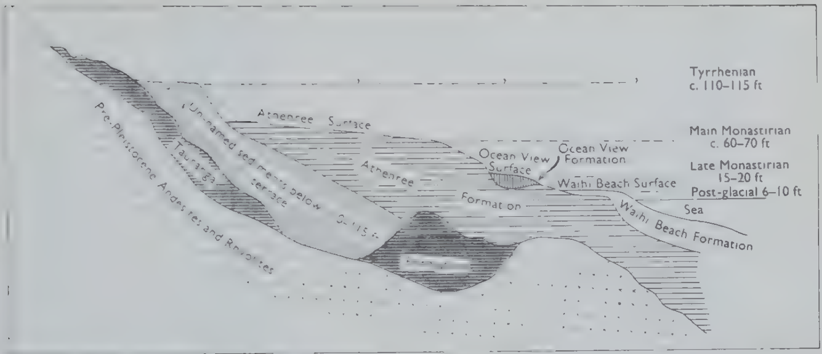

FIG. 4—Idealised diagram of surfaces and formations at Waihi Beach, together with their indicated sea levels, heights, and correlations.

Pre-Pleistocene

The Quaternary rocks of the Waihi Beach area rest unconformably upon late Tertiary rhyolites and andesites that are typical of the Cape Colville Peninsula succession, and form rugged hills inland (Figs. 5, 6).

Older Pleistocene

Morgan (1924, p. 16) recorded that, near Homunga Bay (2 miles north of Waihi Beach, Fig. 1), "there are wave-cut benches at about 160 ft (indistinct), 340 ft, and 550 ft". The higher benches are badly slumped in the andesitic cliffs, and their heights were remeasured recently as 550 ft and 390 ft above sea level. The 160 ft bench was not relocated.

South of Waihi Beach settlement, highly pumiceous sediments are exposed in road cuttings to the south of the Waiau River, about a mile inland from the sea (at "4", Fig. 2). They are overlain, probably unconformably, by younger terrace beds, and may be correlated with Henderson and Bartrum's (1913, pp. 75–7) Tauranga Beds (now Tauranga Formation). The age of the aggradational surface that these beds underlie is uncertain from evidence at Waihi Beach, but is presumably at least as old as Tyrrhenian (compare the 120 ft surface upon the beds at Kauri Point, Katikati) and might well be older. In Mr Tonge's drillhole (at "1", Fig. 2), clay with peat and timber layers, possibly of the Tauranga Formation, was reported from 95 to 145 ft below present sea level.

Inland of Waihi Beach shopping area, accordant ridge tops are the sole remnants of an eroded surface at 110 to 115 ft, which is underlain by white clays with angular locally-derived rock fragments (Fig. 5). Elsewhere in the Waihi Beach area there is no other undoubted remnant of this surface, although inland of the remnants of the Athenree Surface, the spurs and ridges rise irregularly, but not steeply, to the main hills (formed of volcanic rocks). These areas are probably underlain by Pleistocene sediments that were originally below an aggradational surface, only a little higher than the Athenree. They have since been considerably eroded. The weathered clays and conglomerates that are exposed at the Athenree junction on the

Waihi-Tauranga road (Fig. 2) may be representative of them. Insufficient is known of these older beds to name them formally, and they are accordingly styled broadly as "Older Pleistocene".

Athenree Surface and Formation

From a point half a mile north-east of its junction with the Waihi-Tauranga Main Highway, the road towards Athenree settlement is formed along a sloping terrace surface for a distance of just over a mile. This constitutes the type locality of the Athenree Surface. It terminates to the north at a Maori pa (Fig. 2), a little under a mile north-west of Athenree settlement, from which the name is taken.

The distribution of the Surface is shown in Fig. 2 and its form illustrated in Fig. 6. Its minimum height is now 70 ft; and three profiles (Fig. 3, CD, EF, and KL) show that, if extrapolated, the Surface would intersect the present coastline at 62–68 ft, 68 ft, and 60–70 ft in different parts of the Waihi Beach area. The sea level controlling its formation was certainly 70 ft or lower, and was probably between 60 and 70 ft. It could, however, have been lower than 60 ft.

The slope at right angles to the coast appears reasonably constant over the sections measured, and was determined as 30 to 40 ft per mile ($\frac{1}{2}°$). The degree of preservation of the Surface, between Athenree Settlement and Waihi Beach, is highly variable along different lines parallel to the coast; but it is roughly estimated that about 15% of the original terrace surface length remains uneroded.

The Athenree Formation has the same name derivation and type section as the Surface. It comprises light clayey sands overlain by thoroughly weathered reddish-brown clays that may, in part, be volcanic ashes. White clay, with volcanic and carbonaceous fragments, is well exposed at the Bowentown turn-off from the main Waihi highway at Waihi Beach (at "2", Fig. 2).

Ocean View Surface and Formation

Ocean View Road at Waihi Beach (Figs. 2, 2A, and 3) has been constructed predominantly along a sloping surface that is eroded at its seaward end. It constitutes the type locality of, and gives it name to, the Ocean View Surface (distribution, Fig. 2). Extrapolation of profiles AB and IJ (Fig. 3) shows intersections with the present coastline at 15 to 20 ft above mean sea level. A typical view of the surface is shown in Fig. 6 (b).

Somewhat better evidence of the height of contemporary sea level is given by an occurrence of the Ocean View Surface, 22 ft above sea level, 20 chains along the Bowentown road from the main Waihi highway (at "3", Fig. 2; section IJ, Fig. 3). A hillock, immediately seaward of this point, is composed of white clay, typical of the Ocean View Formation elsewhere, overlain by sands. The interpretation is that the sand represents a coastal dune or beach ridge immediately seaward of Ocean View alluvial flats. Similar deposits, showing the same mutual arrangement, may be

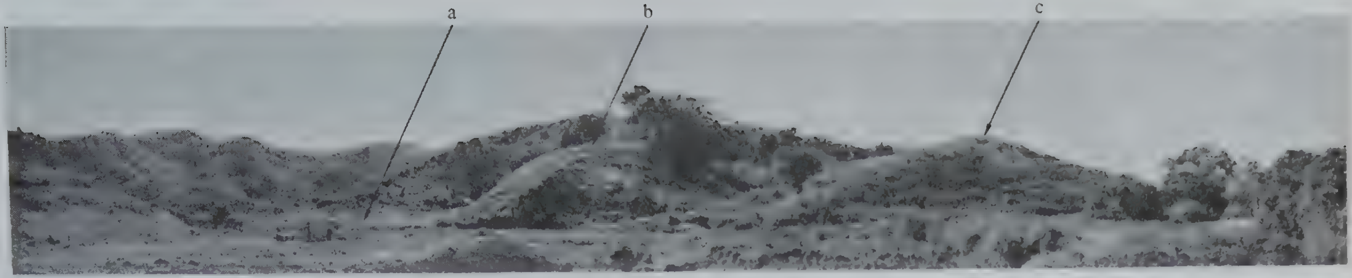

FIG. 5—Ocean View Terrace surface (a) extending up the valley of a small creek at the western end of Ocean View Road ("5" on Fig. 2). Two remnants of the Tyrrhenian surface (110-115 ft A.S.L.) show in spurs (b, c). The hills behind are pre-Pleistocene Andesites.

FIG. 6—Athenree (a) and Ocean View (b) surfaces from Waihi - Waihi Beach road ("6" on Fig. 2); panorama taken in south-east quadrant. High pre-Pleistocene hills (c) show to right, and Waihi Beach alluvium on the left (d).

observed in the present-day cycle in the lower Waiau Valley where the level of the flats is 4 to 5 ft above present sea level. This would imply a sea level of approximately 15 to 20 ft (strictly 17 to 18 ft on these figures) at the time of formation of the Ocean View Surface.

The slope of the Surface is highly variable, ranging from 10 to 60 ft per mile in different sections. Such variation, when compared with the relatively constant slope of the Athenree Surface, no doubt reflects the fact that, while the latter originally extended virtually unbroken from Waihi Beach to Athenree, the Ocean View Surface has been confined to valleys cut in older sediments. It can, for example, be traced from its type locality up the winding valley of a small stream (Fig. 5), as a steeply-sloping alluvial fan. Its slope was therefore dependent upon local variations in supply of sediment and water. Its degree of preservation is less easily determined than for the Athenree Surface, but measurements parallel to the sea suggest that roughly 30% of the length of the original terrace surface remains.

The Ocean View Formation has the same type section and name derivation as the Surface. Its lowest exposed bed is in most places a white unweathered clay. This is generally overlain by sandy clays, but by conglomerates near Waiau River, all of which (including conglomerate pebbles) are very weathered, and brown in colour. Near Waihi Beach township, the sandy clays contain angular rock fragments (commonly $\frac{1}{4}$–$\frac{1}{2}$ in.; rarely 2 in.) derived from the volcanic hills close behind. Sand dunes are present locally, usually on the landward side of present day dunes, but in some places forming the cores of the highest of the latter. The surface beds of these dunes are highly weathered, and are brown and clayey, but 15 ft or so below the surface they grade down to brown clayey sands that are markedly less weathered.

In many areas the formation is overlain by a few feet of less weathered sand that is slightly younger than the bulk of the formation.

Differentiation of Athenree from Ocean View sediments is difficult, and may indicate that the Ocean View Surface represents a still-stand during the fall in sea level from that which gave rise to the Athenree Surface, rather than that a period of low sea level separates the two. The former solution is implied in Fig. 4.

Waihi Beach Surface and Formation

A near-flat surface exists close to the sea at Ocean View Road (6–9 ft above sea level, AB, Fig. 3), and constitutes the type locality of the Waihi Beach Surface. Similar flat surfaces exist at Tauranga Harbour (7 to 10 ft, GH, Fig. 3), and at the Waihi Beach shopping area (where a thin sand layer has built the surface to as high as 12 ft). These surfaces, which show hardly any sign of erosion, are presumed to indicate an old sea level, 6 to 10 ft above the present. Inland, some low terraces, close to the present flood plain and presumably of Waihi Beach age, are more eroded, but more than 50% of the width of the original surface remains.

Over much of the length of the beach, for two miles from its northern end at Waihi Beach, the surface is cut on brown clays of the Ocean View or older formations. Holocene dune and beach sand overlies, but the clay has been re-exposed locally by bulldozing or by the severe marine erosion of recent years.

All post - Ocean View aggradational sediments are included together in the Waihi Beach Formation. Differentiation on an age basis requires even more detailed treatment (cf. Schofield, 1960) than was afforded in the present survey. Thus the formation comprises swamp, alluvium, dune sand, and estuarine muds.

Prominent dunes, now fixed by lupin, rise to a maximum of about 35 ft, and average 15 to 20 ft above sea level. The highest hills (in the south-east) have a core of older sand dunes of the Ocean View or older formations. Nine post-hole bores, forming part of an ilmenite survey by Messrs H. E. Fyfe and D. S. Nicholson and the present authors (*see also* Nicholson *et al.*, 1958), average 13 ft in depth, 5·9% ilmenite, and 34% TiO_2 in the ilmenite. Table 2 gives the detailed results for the holes shown in Fig. 2.

TABLE 2—Details of Blacksand Boreholes

Hole	Distance from H.W.M. (yds)	Depth (ft)	Ilmenite (%)	TiO_2 in Ilmenite (%)	Remarks
A1	255	20	6·5	n.d.	Yellow clayey sand 10–20 ft.
A2	155	7½	9	n.d.	Includes 1 ft of rich blacksand.
A3	55	9½	14	40	Slightly blacker 5½–9½ ft.
B1	290	17	8	n.d.	Pumice bed at 11 ft. Iron pan at 13 ft.
B2	190	13¾	1	27·2	Rich blacksand 9–10 ft.
B3	90	20	3	n.d.	
C1	10	13	5·5	n.d.	
C2	150	10	1·5	n.d.	Pumice at 6 ft.
C3	340	8½	5	34·4	Iron-staining 4–7 ft.

All boreholes except A1 finished in water (presumably close to sea level) when caving prevented further boring. Analysts: D. S. Nicholson and J. J. Cornes.

Thin pumice beds were found within the sand-dunes in two of the nine holes (C2 and B1), 6 ft and 11 ft below the surface, and probably 4 and 6 ft above sea level. Bore A1 was put down in the highest dune ridge. It penetrated to the older yellow clayey dune sand at 10 ft.

Blacksand is locally present on the modern intertidal beach, which is being actively eroded at its north-western end beside Waihi Beach township.

A coastal terrace, on which Athenree settlement is built, descends to a level of 10 ft above mean sea level. Since the sediments immediately beneath it are brown and clayey, they are referred to the Ocean View Formation; but their upper surface is presumed to have been cut, and is correlated with the Waihi Beach Surface.

CORRELATION AND STABILITY

Evidence that the terrace surfaces at Waihi Beach were formed during interglacial rather than glacial times is indirect. First, the topographic setting of the older-cycle Ocean View Surface is very similar (*see* Fig. 2) to that of the younger-cycle Waihi Beach Surface, which is itself undoubtedly interglacial. Secondly, except near the courses of the main river valleys and close to hills of volcanic rocks, where coarser material is to be expected, the sediments are relatively fine grained, and clayey sands are typical. Thirdly, similar surfaces at South Kaipara, also without marine fossils, have been recognised as interglacial by Brothers (1954). It is therefore concluded that the terraces were formed during interglacial periods, and that their surfaces may be correlated with eustatic sea levels.

Table 1 shows that the sea-levels indicated at 6–10 ft, 15–20 ft, c. 60–70 ft, and c.110–115 ft, may be correlated with the Post-glacial, Late and Main Monastirian, and Tyrrhenian eustatic sea levels respectively. The c.340–390 ft and c.550 ft slumped rock benches at Homunga Bay may be considered indicative of the Sicilian and Calabrian sea levels, although the degree of certainty is less. There is such close agreement between the levels of surfaces at Waihi Beach and those of the stable South Kaipara area (Table 1) that the conclusion seems inescapable that the Waihi Beach area also has been relatively stable in at least late Pleistocene time.

OTHER NEARBY COASTAL TERRACES

Bell and Fraser (1912, p. 29) record four distinct terraces in Orakawa Bay, a mile north of Waihi Beach (Fig. 1). Three were measured recently as 6 ft, 10–15 ft, and 25–35 ft above sea-level. The 6 ft terrace, composed of loose sand, which is actively being eroded by the sea, contains two Maori midden layers, 18 in. apart, which include shells and charcoal. This terrace is clearly younger than the 6–10 ft Post-glacial level(s). Its comparatively high level may well be due to the observable increased wave activity, which probably also causes the comparative steepness of the present beach there. Thus the two higher surfaces (10–15 ft and 25–35 ft, in sand and gravel) probably represent the Post-glacial and Late Monastirian sea levels, which are each similarly slightly higher than at Waihi Beach. A shell bed up to 1 ft thick, about 6 ft above mean sea level, is composed, predominantly, of broken and crumbling shells of *Struthiolaria papulosa*. It is exposed very locally on the face of the 10–15 ft terrace, and is obviously younger than the latter. Its brown clayey sand matrix suggests that it is older than the Maori middens. No charcoal was seen in it, nor in two similar deposits, one on either side of Whitianga Harbour to the north (national grid references N44/196659 and N44/213630, Fig. 1). It is uncertain whether human agency was involved in the deposition of these beds, or whether *S. papulosa* was temporarily more common in some Post-glacial time, than it is at present. Its shells are present on modern beaches in the area, but are far from predominant.

At Homunga Bay, 1¼ miles north of Orakawa, wave-cut-platform remnants at 10–12 ft and 25–30 ft again probably represent the Post-glacial and Late Monastirian levels (i.e., they would be correlated with the Waihi Beach and Ocean View Surfaces, but would be slightly higher).

Terraces are present at 3 ft, 6–9 ft (with dunes on it), 18 ft, and 24 ft at Opoutere, 8 miles north of Whangamata and 30 miles from Waihi Beach (Mr H. E. Fyfe, pers. comm.). The former two would correspond with the lowest two terraces at Orakawa Bay. The 18 ft and 24 ft terraces, which are extensive inland around Opoutere, would together represent the Late Monastirian. They are underlain by clays with rare sand and gravel beds.

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OCCURRENCE OF PENTLANDITE IN NEW ZEALAND

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(Received for publication, 27 February 1961)

Abstract

Pentlandite is recorded from a poorly known occurrence of sulphide ore on the Takaka River in the northern part of the South Island of New Zealand. The ore is a typical pyrrhotite-pentlandite-chalcopyrite association comparable in paragenesis and mode of occurrence with the nickel ores of Sudbury (Ontario), Insizwa (South Africa), and elsewhere. The ore is rich, but the known extent of the lode is too small for it to be of economic value. Suggestions are made for future exploration.

INTRODUCTION

Nickeliferous sulphide ore is exposed in a cutting on the west side of a road leading to an asbestos mine in heavily bushed country some 2½ miles from the junction of the Cobb and Takaka Rivers in north-west Nelson (N.Z.M.S. 1, S13/105498 [1950]). The occurrence was noted some twenty years ago when field examination by the New Zealand Geological Survey indicated the existence of several lens-shaped magnetic ore bodies ranging up to a maximum of 10 ft in width but with "small linear extent" (Wellman, 1941, p. 12). An assay by the Dominion Laboratory proved the presence of appreciable nickel and cobalt in the ore.

Recently, Lime and Marble Ltd., of Mapua, Nelson, have taken an active interest in the occurrence, and at their request independent mineragraphic reports were submitted by the present authors during the latter part of 1959 and the early part of 1960.* This contribution combines the work of each.

MINERALOGY AND NICKEL CONTENT OF THE ORE

The country rock that is host to the ore lenses is an altered basic igneous rock. It consists essentially of an interlocking network of partly altered plagioclase (near An_{40}), amongst which are aggregates and individual needles of pale green actinolitic amphibole and small amounts of epidote. The texture and mineral assemblage is that of a uralitized dolerite. Unevenly distributed through this rock are small veinlike segregations of sulphide minerals associated with more than usual amounts of epidote. The main sulphide mineral is pyrrhotite partly altered to limonite and hematite, but there is also 3–4% of chalcopyrite in grains 0·01 – 0.25 mm in diameter. No pentlandite was observed in this association.

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*Specimens were collected by Messrs D. P. Bullen and J. C. Braithwaite, the company prospector and geologist respectively.

N.Z. J. Geol. Geophys. 4 : 446–48

The texture and mineral composition of the large lenses of ore differ from that of the thin veins and disseminated granules of the country rocks. This ore consists of an irregular granular intergrowth of pyrrhotite, pentlandite, chalcopyrite, and about 30% of silicate gangue, which is mainly intergrown epidote and actinolite with subordinate feldspar (Fig. 1). Pyrrhotite forms about 60% of the ore. It varies in size from aggregates 1–2 mm across, each of which consists of several individual crystals, down to tiny granules scattered through the silicate gangue. Pentlandite (up to 10%) occurs as veinlike bodies 0·1 mm in width or as isolated grains up to 0·75 mm across, enclosed within the aggregates of coarser-grained pyrrhotite. The texture is identical to that of pyrrhotite-pentlandite-chalcopyrite ores from elsewhere (e.g., Sudbury; *see* Ramdohr, 1960, p. 465) and is similar to the texture obtained experimentally by allowing pyrrhotite-pentlandite solid solutions at high temperature to unmix slowly on cooling (Hawley and Haw, 1957). Chalcopyrite constitutes no more than 1% of the ore. Relatively large grains (0·2 mm) occur sporadically within and around the large pyrrhotite crystals, and tiny grains are found disseminated in the silicate gangue.

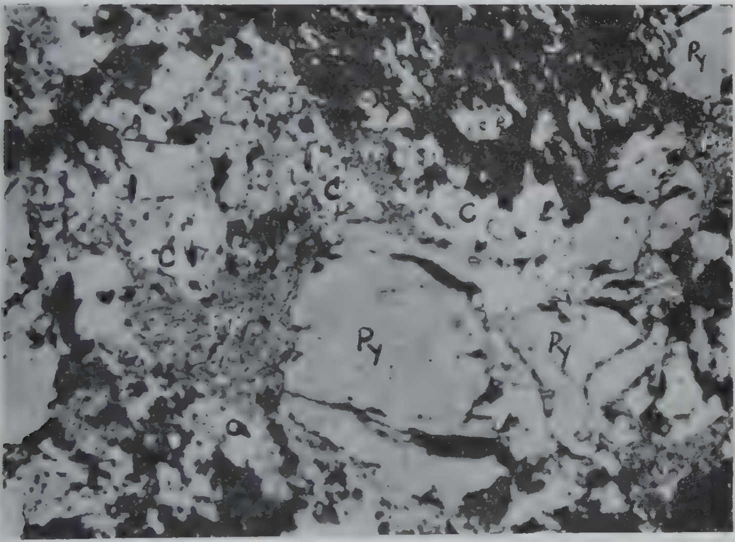

Fig. 1—Photomicrograph of the Takaka pyrrhotite-pentlandite-chalcopyrite ore. Chalcopyrite (C), white; pyrrhotite (Py), light-grey; pentlandite (Pt), dark grey; silicate gangue, black. (Reflected light, × 165.)

The presence of granular and veinlike bodies of pentlandite amongst pyrrhotite suggests that the pentlandite has unmixed and segregated from a pentlandite-pyrrhotite solid solution and that the pyrrhotite may still contain appreciable amounts of nickel in solid solution. This was confirmed qualitatively by use of contact electrographic print techniques, which gave a positive nickel reaction over areas of polished surface of pyrrhotite where granular pentlandite was absent.

Portion of an ore lens was ground to −100 mesh, and separated into two fractions, a pyrrhotite-rich magnetic fraction and a pentlandite-rich non-magnetic fraction, by using a hand magnet and a Franz Isodynamic Separator. The mineral compositions of these fractions were determined by micrometric analyses carried out on polished briquettes of the ground and separated material. These results together with the respective nickel contents determined by X-ray spectroscopy are given below in weight percentages:

	Original Material	Magnetic Fraction	Non-Magnetic Fraction
	%	%	%
Pyrrhotite	63	95	—
Pentlandite	9	3	35
Chalcopyrite	1	tr.	3
Silicate Gangue	27	2	62
Nickel	3	2	8·6

The proportion of nickel in the pentlandite and pyrrhotite may be calculated from these values on the assumption that only these two minerals contain nickel and that the average specific gravity of the mixed sulphides is 3·75. Thus, the pentlandite contains about 25% Ni and the pyrrhotite retains 1·3% Ni in solid solution. The nickel content of the ore (3%) is therefore distributed between pentlandite and pyrrhotite in the proportion 73:27.

CONCLUSIONS

The ore is comparable in texture, mineral composition, nickel content, and mode of occurrence with typical pyrrhotite-pentlandite-chalcopyrite associations elsewhere, as at Sudbury (Ontario) and Insizwa (South Africa) (Vogt, 1923; Wilson, 1953). As at these economically important localities, the ore occurs within a basic igneous rock, and the larger masses are best explained as segregations within this rock.

Although specimens are rich in nickel, the known ore body is not economic because of its very small size. However, the exposure occurs in mountainous, thickly wooded country, and it is not unlikely that further search would reveal more ore lenses. The economic potential of the field could be assessed by determination of the extent of the basic igneous host rock, followed by magnetic and geochemical prospecting for disseminated granular or larger lenticular ore bodies.

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STRATIGRAPHY AND STRUCTURAL OUTLINE OF THE TAUPO VOLCANIC ZONE

By Roger C. Martin, Victoria University of Wellington*

(Received for publication, 3 November 1960)

Abstract

The Taupo Volcanic Zone is a complex basin of volcano-tectonic subsidence in the central North Island. Here eruptive activity has persisted from approximately mid-Pliocene to the present time. It is a basalt-andesite-rhyolite volcanic province well known, for its ignimbrites, for the rocks are dominantly stratiform rhyolitic pyroclastics, and of these, welded ignimbrites are the most conspicuous. Massive rhyolite domes and andesite volcanoes are common, but associated dacites and basalts sparse.

The ignimbrites are widespread, easily recognized stratigraphic units, which form the basis of stratigraphic subdivision. Except for surficial pyroclastic deposits, the ignimbrite sheets are the only rock units in the volcanic zone that can be distinguished from one another on the basis of lithology and mineral composition, and hence can be correlated over large distances. The ignimbrites average 100 ft in thickness and many have extended over areas exceeding 1000 sq. miles.

The following litho-stratigraphic units, in order of increasing age, are described here:

- Mamaku Ignimbrite
- Whakamaru Ignimbrites⁺
  - Maraetai Member
- Manunui Ignimbrites
- Huka Group⁺
  - Kaingaroa Ignimbrites⁺
  - Matahina Ignimbrite
  - Atiamuri Ignimbrite
  - Waiotapu Ignimbrite⁺
  - Marshall Ignimbrites
    - Taupaki Member
- Rocky Hill Ignimbrite
- Waitaha Group
  - Te Whaiti Ignimbrites⁺
  - Rangitaiki Ignimbrites⁺
- Ahuroa Ignimbrites
- Ongatiti Ignimbrite
- Ranginui Ignimbrite
- Paeroa Range Group
  - Paeroa Ignimbrites⁺
  - Te Weta Ignimbrites
  - Te Kopia Ignimbrites⁺
- Ngaroma Ignimbrite

These are all newly named, except for those marked ⁺, which are redefined or modified from earlier literature.

On the basis of surface exposure, the ignimbrite formations appear segregated into three areas: a western "fringe" or apron, a down-faulted central area, and an eastern marginal area. The western ignimbrites are mainly old, thin, but extensive sheets veneering an apron of Tertiary and Mesozoic sediments extending west from the Rangitoto and Hauhungaroa Ranges. The ignimbrites in the central area vary widely in age and are interbedded with thick sequences of tuffs and tuffaceous sediments, such as those of the Huka Group. The eastern ignimbrites cover the extensive Kaingaroa Plateau and fill valleys along the high Te Whaiti greywacke ranges to the east. The oldest of these are down-faulted and now deeply buried in the central area.

Numerous unconformities and irregular gravity profiles testify to a complex volcanic history in which periods of highland erosion and lowland sedimentation were frequently interrupted by large-scale ignimbrite eruptions. Lateral gradations in several ignimbrites suggest that they were erupted from different parts of the Taupo Zone, each presumably from vents tapping a separate magma chamber at depth. Following each voluminous eruption, piecemeal collapse occurred, partly along normal faults,

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*Formerly with the New Zealand Geological Survey. This paper was sponsored jointly by the Survey and the University.

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contributing to the formation of subsidence areas such as the Mangakino Basin, Lake Taupo, and others within the Taupo-Rotorua Graben. Displacements of the order of 1500 ft or more are shown by the Paeroa and Rangitaiki Faults.

Proven ignimbrite feeder dikes or vents have not yet been recognised, and it appears that most of those in the Taupo Volcanic Zone are in areas that have undergone maximum subsidence and burial.

INTRODUCTION

The Taupo Volcanic Zone extends as a belt widening north-eastward from the Tongariro volcanoes to the Bay of Plenty (Fig. 1). The Taupo Zone volcanic rocks include late Pliocene to Recent lavas and pyroclastics ranging from basalt to rhyolite (Grange, 1937). Andesite volcanoes and rhyolite domes are common, but the bulk of the rocks are stratified, consisting of interbedded ignimbrites (welded rhyolite tuffs and similar pyroclastics) and tuffaceous sediments. Many of the ignimbrite units are widespread and lithologically distinctive sheets, useful as stratigraphic markers. The rocks described here cover all but the extreme southern and northern parts of the zone.

The main object of this study has been to work out the succession of volcanic strata across a large part of the Taupo Zone (Fig. 4) in order to help elucidate the structure of the area. This paper is preliminary, and only broad aspects of the stratigraphy and structure are presented. For convenience of description the Volcanic Zone is divided into western, central, and eastern areas.

Previous Work

The stratified volcanics of the Rotorua-Taupo subdivision were mapped by Grange (1937), but only major rock units such as "lacustrine and fluviatile beds" and the "Patetere ignimbrite and breccia" were differentiated.

Similarly the ignimbrites of the Te Kuiti district were all included in the "Ignimbrite Series" by Marwick (1946). He was one of the first to mention the possibility of erosion or deposition between successive ignimbrite eruptions.

Mapping of separate ignimbrite sheets, notably the Kaingaroa and Rangitaiki ignimbrites, was initiated by L. R. Allen (formerly of N. Z. Geological Survey) on the Kaingaroa Plateau. Though this work was not finished, much has been incorporated in later mapping and stratigraphic study of the eastern area.

In the Wairakei area the stratified volcanics were subdivided and mapped by Beck (Beck and Robertson, 1955). In the Waiotapu area, farther north, five key ignimbrite formations were mapped and described by Grindley (1959).

Related stratigraphic study of the recent ash-fall pyroclastics is more advanced than that on the underlying consolidated volcanics. Detailed studies have been made by Baumgart (1954), and a regional study of the ash stratigraphy is in preparation by Messrs J. Healy, W. A. Pullar, and C. G. Vucetich.

The main structural features of the Taupo Zone have been outlined by Marwick and Fyfe (1937) and also by J. Healy in unpublished Geological

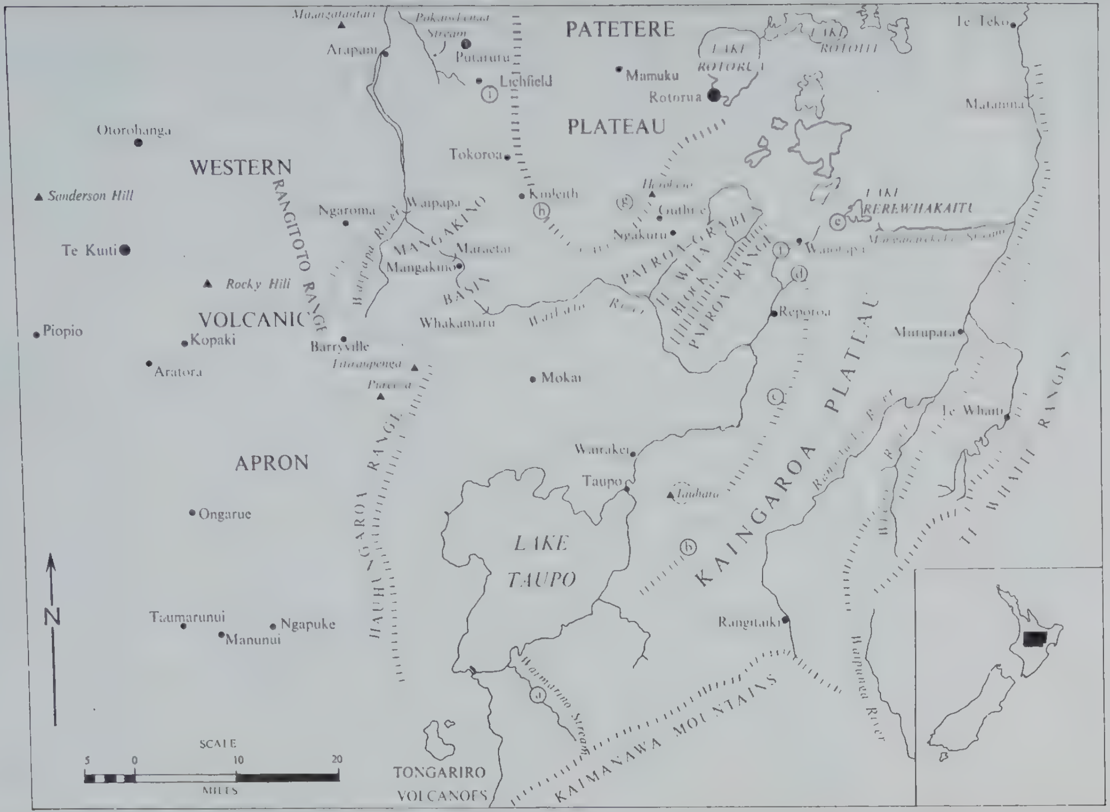

FIG. 1—The central Taupo Volcanic Zone and surrounding area. Circled letters indicate locations of specimens represented in Fig. 2.

Survey reports. The recent geophysical surveys and interpretations of Modriniak and Studt (1959) have brought important advances in the understanding of subsurface structure in this area.

STRATIGRAPHY

TERMINOLOGY AND STRATIGRAPHIC METHODS

In defining stratigraphic units, the Australian Code of Stratigraphic Nomenclature (1959) has been followed as closely as possible.

The basic stratigraphic unit in the Taupo Zone is commonly the *ignimbrite sheet,* or simply "ignimbrite", which is the sheet or tongue-like deposit of a single* pyroclastic flow, or glowing avalanche type eruption. As a formal litho-stratigraphic term, "ignimbrite" is useful, yet relatively new. Probably the first rock units named with this term were the Whakamaru Ignimbrites (Hatherton, 1954), and the Wairakei Ignimbrite and Kaingaroa Ignimbrite (Beck and Robertson, 1955). Previously the term "tuff" has been used in stratigraphic names, e.g., "Mamaku Tuff". As pointed out by Cook (1960), however, tuff, in that context, does not convey to the reader an image of what the material may be, whether compact ash, felsitic welded tuff, or even water-laid, bedded tuff.

Some thick and extensive ignimbrites are lithologically distinct, mappable units designated as *formations.* Other formations consist of multiple deposits, or stratified groups of lithologically similar ignimbrites. In both cases the formations described here generally represent distinct periods of volcanicity.

A *member* is a lithologically distinct division of a formation, and commonly refers here to a single ignimbrite. Examples are the "Taupaki Member of the Marshall Ignimbrites" and the "Maraetai Member of the Whakamaru Ignimbrites".

Some ignimbrite formations (e.g., Kaingaroa Ignimbrites) consist of two members, lithologically distinct, but locally gradational and petrographically very similar. Because of their close genetic relations (probably formed by closely following eruptions from the same magma chamber) these members are not given separate geographic names, but simply designated "upper" and "lower". Examples are the "upper Kaingaroa Ignimbrite" and the "lower Kaingaroa Ignimbrite".

Group designations are given to sequences of two or more ignimbrite formations having common petrographic features but which are not separated by major unconformities. Examples are the "Paeroa Range Group" and the "Waitaha Group".

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*Some ignimbrites are found, under detailed examination, to consist of two or more gradational layers deposited not by a single pyroclastic flow, but by successive flows produced in spasms of one main eruption. These multiple deposits cooled as single units and are here treated as such stratigraphically. They are called *compound ignimbrites.* Examples are the Maraetai, Waiotapu, and possibly the Ongatiti and Matahina sheets.

Several other stratigraphic units have been defined by Smith (1960) in a comprehensive paper that has come to the writer's attention since this manuscript was submitted. Smith's term *cooling unit,* "a single or multiple ash-flow deposit that can be shown to have undergone continuous cooling", is particularly descriptive of the New Zealand rocks, including both the simple and compound ignimbrites described here.

Correlation of Units

Correlation of units is established by: (1) position in a stratigraphic sequence, (2) continuity of outcrop, (3) lithology, and (4) crystal fragment composition. These criteria have been applied in Nevada and Utah by the co-workers Cook (1957) and Mackin (1960). In the North Island, as in Nevada and Utah, ignimbrites are continuous gently-dipping sheets, many of which can be traced almost continuously for tens of miles.

Utility of Mineral Histograms

Traced laterally, ignimbrites may vary greatly in texture and degree of welding, but the assemblage of crystal fragments (phenocrysts erupted from depth) remains relatively constant throughout a single deposit. This provides a useful basis for correlation, especially in the absence of field evidence. Crystal composition was at first determined by examination with a binocular microscope of rock slabs etched and stained with $Na_3Co(NO_2)_6$ solution (used to facilitate potash feldspar determination), in the manner used by P. L. Williams (1960). Because many of the New Zealand ignimbrites differ only slightly in crystal composition, the writer modified this technique to the more laborious but more precise method of modal analysis with a point counter on large etched and stained thin sections. This method allows more positive identification of minor constituents, such as quartz, mafic, and accessory minerals.

For ease of comparison, the resulting data were plotted in graph form similar to that used by Williams (1960). The histograms (a)–(e) of Fig. 2 show the constancy of crystal content of an individual ignimbrite at widely-spaced localities. Histograms (f)–(i) represent the same qualities in a different sheet. These illustrate (1) the distinct difference in crystal content between the two ignimbrites, and (2) the average variation in crystal content to be expected in a single unit. Non-phenocrystic minerals, such as microcrystalline tridymite and cristobalite, which formed in place, are not plotted.

Representative histograms of the principal ignimbrites of the southern and central Taupo Zone are shown in Fig. 3. They are arranged in stratigraphic order, with the Rocky Hill, Mamaku, and Kaingaroa Ignimbrites heading columns representing the western, central, and eastern areas respectively.

Limitations of Histogram Correlation

Some histograms are of negative rather than positive value for correlation. That is, specimens having the same mineral composition may or may not represent the same sheet, but two specimens having radically different mineral compositions may confidently be assumed to represent different sheets. Thus, in Fig. 3 the similarities of the Ongatiti, Rangitaiki, and Te Kopia Ignimbrites in one group, and of the Waiotapu, Ahuroa, and Kaingaroa Ignimbrites in another group, are merely coincidental. They can all be shown to be stratigraphically distinct units by lithology and field evidence.

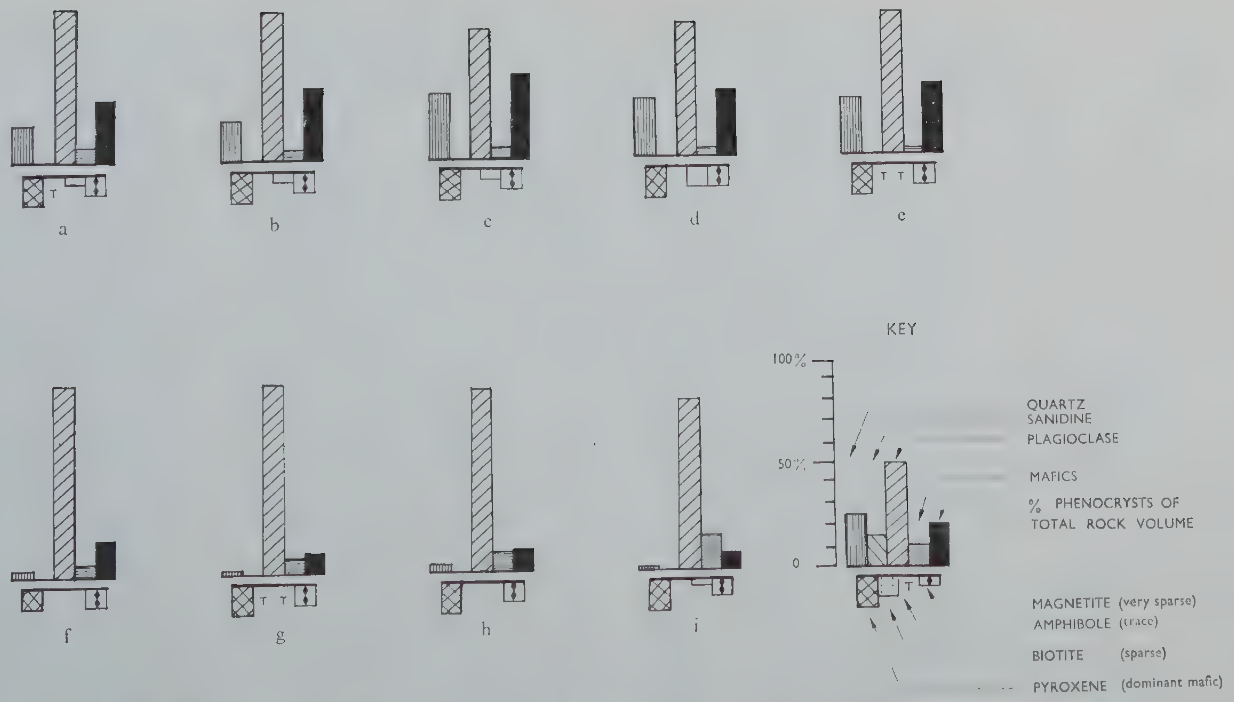

FIG. 2—Mineral histograms showing uniformity of phenocryst composition at widely spaced localities. Specimens a-e taken from the upper Rangitaiki Ignimbrite at random intervals spanning 55 miles. Specimens f-i from the Waiotapu Ignimbrite over a span of 35 miles. Letters in Fig. 1 mark localities of specimens.

Mineral species are plotted in the upper histograms as per cent of total phenocrysts. Small inverted histograms show only approximate proportions of mafic crystals. Trace quantities are indicated by "T".

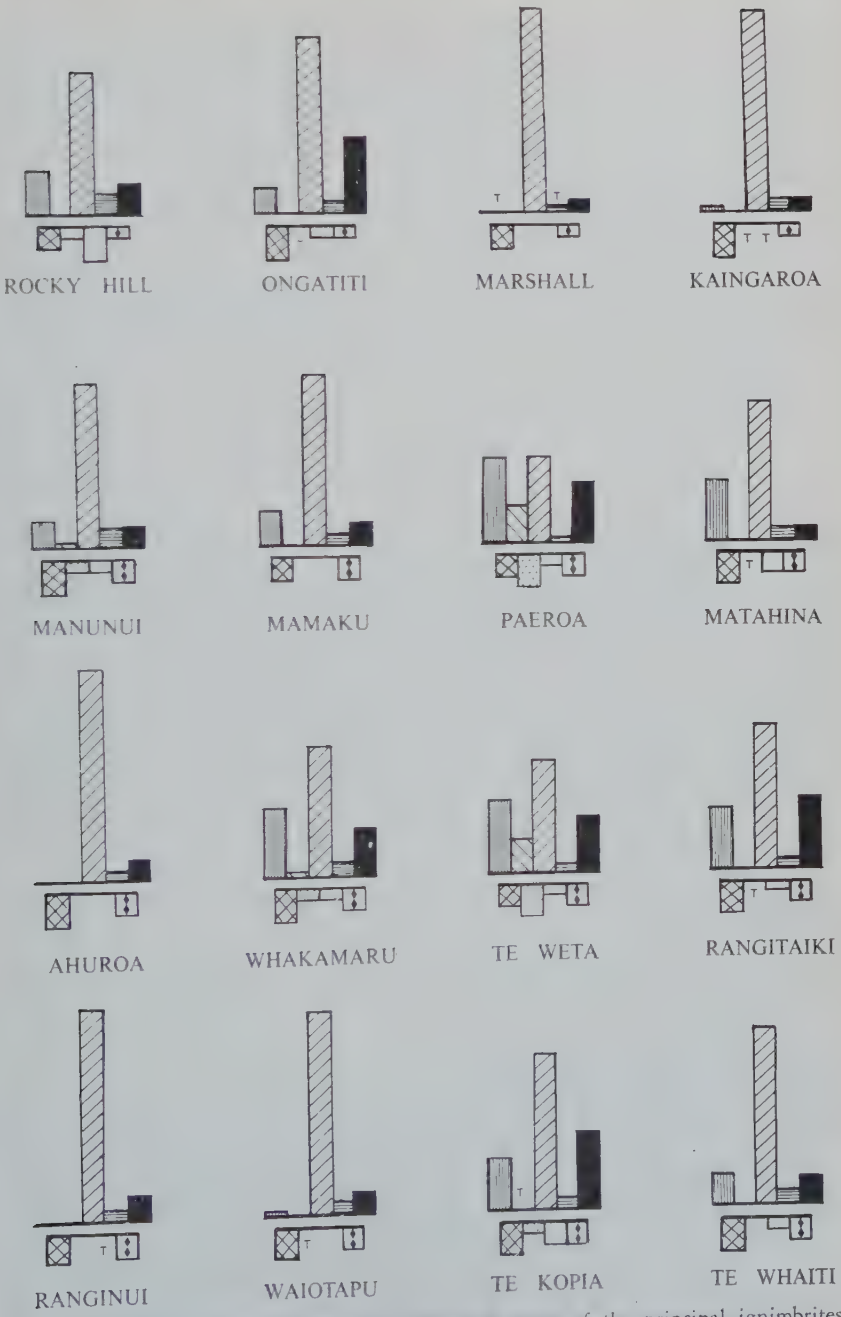

FIG. 3—Phenocryst (crystal fragment) content of some of the principal ignimbrites of the Taupo Zone, illustrated graphically. See Fig. 2 for key.

Phenocryst Composition of the Ignimbrites

As shown in Fig. 3, plagioclase, magnetite, and pyroxene are ubiquitous. Plagioclase is commonly in the andesine range. Common hypersthene is the dominant pyroxene, and augite is rare. Quartz comprises as much as 40 per cent of the phenocryst volume of crystal-rich ignimbrites, but is rare in the highly-welded vitric types.

Sanidine is relatively rare in the ignimbrites of the Taupo Zone, and has been useful for correlation of a few sanidine-bearing formations. It has been found only in the massive, non-lenticulitic rocks of the Whakamaru, Manunui, and Paeroa Range Group ignimbrites. Zircon, the most common minor accessory, appears most abundant in the ignimbrites of the eastern part of the Zone, notably the Rangitaiki, Te Whaiti, and older lenticulitic ignimbrites.

WESTERN AREA

General Features

Beyond the western boundary of the Taupo Zone a thin westward-sloping apron of stratified ignimbrites rests on Mesozoic and Tertiary sediments of the north-trending Hauhungaroa and Rangitoto Ranges and adjacent area. This volcanic apron is a relatively stable fringe area representing the western part of a high plateau or up-arched surface, the central part of which has since collapsed to form the complex graben structures of the Taupo Volcanic Zone.

The eastern scarp of the apron is highly eroded and partly overlapped by the young Whakamaru Ignimbrites which blanket the down-faulted older ignimbrite terrain east of the scarp. The ignimbrites of the western apron generally dip about 2° west.

Ignimbrites of the Western Area

The following succession of formations is recognised in the western King Country area:

Rocky Hill Ignimbrites
Manunui Ignimbrites
  Unconformity
Ahuroa Ignimbrites
Ongatiti Ignimbrite
Ngaroma and related ignimbrites

The Ongatiti and Ahuroa Ignimbrites are the most widespread and distinctive of these units. They make up most of the western part of the volcanic apron, and each can be traced laterally for more than 40 miles. The Ongatiti extends farther south, the Ahuroa, farther north. Resting uncomformably on these are the Manunui and Rocky Hill Ignimbrites, which commonly form small outliers on the western part of the apron.

The pyroclastic rocks of the western apron have been referred to collectively as the Mamaku beds (*see* Thompson *in* Fleming, 1959, pp. 206–7), Patetere Series (Grange, 1937), and the Ignimbrite Series

(Marwick, 1946). Lately they have been mapped and formally named the Pakaumanu Ignimbrites by Kear (1960). He designated Rocky Hill as type locality and described four units in that section.

VOLCANIC SEQUENCE AT ROCKY HILL

Lithology	Thickness (ft)	Name
Coarse pumice tuff breccia, welded	75+	Rocky Hill Ignimbrites
Tuffaceous sands, well bedded vitric and chalazoidite tuffs; section only partly exposed	200	Puketoka Formation
Lenticulitic tuff, containing flattened platy pumice fragments	80	upper Ahuroa Ignimbrite
Lenticulite, grey, felsitic, highly welded	20+	lower Ahuroa Ignimbrite
Unseen	50	
Yellow-buff crystal tuff, welded	125+	Ongatiti Ignimbrite
Base not exposed, but nearby consists of Tertiary marine sediments		

These units are named and described here as separate formations. Another ignimbrite formation covering much of the southern and eastern part of the volcanic apron is here named the Manunui Ignimbrites. Wherever studied, the Manunui Ignimbrites have been found to rest with marked erosional unconformity on older ignimbrites and sedimentary rocks. Neither the Manunui Formation nor the underlying unconformity have been recognised at Rocky Hill, but relations at Arapuni suggest that they lie within the sequence, above the Ahuroa and below the Rocky Hill Ignimbrites. Near Barryville, east of Kopaki, the Manunui Ignimbrites rest on a deeply weathered surface of the Ongatiti Ignimbrite, and were considered by Kear (1960) to be post-Pakaumanu in age.

Stratigraphic Grouping of the Ignimbrites

The successive ignimbrite formations of the western apron are widely different petrographically, and are commonly separated by at least minor unconformities. They do not appear to be co-magmatic, nor to fit into groups of lithogenetic significance.

For the purposes of regional mapping, however, it will probably be found convenient to modify Kear's (1960) terminology by defining a new *Pakaumanu Group,* made up of the Ongatiti, Ahuroa, and possibly other ignimbrites older than the pre-Manunui unconformity. This procedure has proved convenient in mapping a part of Sheet 8, south-east of that mapped by Kear (1960). There Grindley (1960) has mapped* two ignimbrite units, an older, pre-Manunui unit consisting mainly of the Ongatiti Ignimbrite, and a second, younger unit embracing the Manunui, Rocky Hill, and Whakamaru Ignimbrites.

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*Based upon more detailed ignimbrite geology in preparation by H. R. Blank, Victoria University of Wellington.

Descriptive Geology of the Western Ignimbrites

The Ngaroma and Ranginui Ignimbrites

In the Ngaroma–Mangakino area a few old, lenticulitic ignimbrites are exposed. As yet little is known of their former extent or detailed stratigraphic position except that they are old and presumably underlie much of the volcanic rocks in the western Taupo Zone. Two are named and described here—the Ngaroma and Ranginui Ignimbrites.

The *Ngaroma Ignimbrite* is the oldest ignimbrite known in the Ngaroma area, where its rests on Mesozoic basement greywacke and underlies the Ahuroa Ignimbrites. It consists of very hard lenticulite, containing thin streaky lenticules in a light blue to pink, felsite matrix. This rock is distinctive for its uniform fine grain and the sparseness and small size of phenocrysts, mainly plagioclase. Small inclusions of grey andesite are conspicuous, though sparse. On the flank of Titiraupenga volcano, 14 miles south of Ngaroma, this ignimbrite rests on basement greywacke, under a tongue of the Whakamaru Ignimbrites. Its type locality is a quarry three quarters of a mile west-north-west of Ngaroma School (N84/055853).

The *Ranginui Ignimbrite* forms much of the high country along the west bank of the Waikato River north of its junction with the Waipapa River. Here outcrops are sparse, but both Ranginui and Ngaroma Ignimbrites appear to underlie the upper platy pumice member of the Ahuroa formation, The Ranginui consists of dense, highly welded, brown and black lenticulite characterised by pronounced hackly fracture, abundant dark lenticules, and clear euhedral plagioclase crystals commonly 3 mm long. The type locality is in the Ranginui Land Development Block on the eastern margin of the volcanic apron, near Barryville (N84/128722). Here it is a thin (30 ft) undulating sheet resting on brown volcanic sand and breccia.

The Ranginui is one of the few western apron ignimbrites that may be identified farther east, in the central area. Unfortunately, its stratigraphic position there is as yet uncertain. Two interpretations of its position are indicated in the second column of Fig. 4—one overlying the Waiotapu Ignimbrite, and the other underlying the Waiotapu and Marshall Ignimbrites.

Ongatiti Ignimbrite

The Ongatiti Ignimbrite (new formation) consists of welded crystal tuff with abundant feldspar, minor quartz, and mafic crystals. It is massive and commonly weathered light yellow. The yellow colour and high concentration of elongate feldspar crystals are distinctive. The Ongatiti can be traced from the east margin of the apron, where it overlies the Ngaroma Ignimbrite and basement greywacke, to the western edge, where it forms cap-rock outliers on isolated hills of Tertiary marine sediments. The Ongatiti commonly underlies the Ahuroa Ignimbrites.

The thickness of the Ongatiti Ignimbrite averages 150 ft. The lower half is hard and massive, containing only rare pumice inclusions and sparse fragments of dense volcanic and Tertiary sedimentary rocks. The upper half is less compact, practically devoid of accidental rock fragments, but highly charged with pumice inclusions that have crystallized to whitish powder.

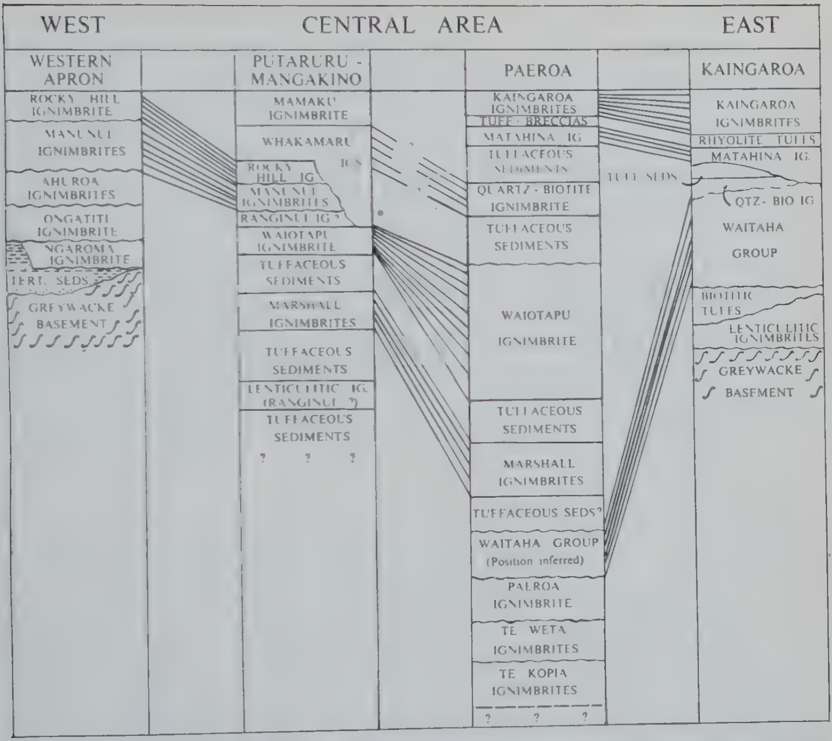

FIG. 4—Generalized succession of stratified volcanics in the west, central, and eastern parts of the Taupo Zone, showing principal ignimbrites used for correlation. Thicknesses are relative: the Paeroa column represents approximately 4,000 ft.

*The relation of the Rocky Hill, Manunui, and Waiotapu Ignimbrites (second column) was not seen; their relative positions shown here have been inferred.

The Ongatiti Ignimbrite is exceptionally well exposed on an irregular erosion surface along the Taumarunui – Te Kuiti highway one mile west of Aratora. Its type locality is above the Ongatiti Stream where the Ahuroa Road descends the southern slope of Rocky Hill, Pakaumanu Survey District (N83/282474).

Ahuroa Ignimbrites

The Ahuroa Ignimbrites (new formation) consist of two lenticulite members lying above the Ongatiti and below the Manunui Ignimbrites. Their type locality is on Ahuroa Road, on the south slope of Rocky Hill, Pakaumanu Survey District. Here the formation is more than 100 feet thick.

Upper Ahuroa Ignimbrite. The upper ignimbrite once covered nearly 1000 square miles of the western King Country between Ngaroma, Sanderson Hill, Aratora, and Maungatautari. At the base of Arapuni Dam, it unconformably underlies the columnar jointed Arapuni ignimbrite

(Marshall, 1935). It contains distinctive yellow to dark grey, flattened pumice lenticules having a distinctive platy internal structure, set in a matrix of grey welded vitric tuff. Plagioclase crystals up to 3 mm long and minor hypersthene and magnetite are inconspicuous, comprising about 8 per cent by rock volume.

Lower Ahuroa Ignimbrite. At Rocky Hill and the bluffs at Rangawhirikaha, 6·5 miles east of Kopaki, the lower ignimbrite consists of tough, dull grey lenticulite having small dark lenticules in a fine-grained lithoidal matrix. Its crystal composition and fabric are similar to those of the upper member. The principal difference between the two is that the upper appears glassier and more tuffaceous, whereas the lower is lithoidal and more highly welded. Weathering reduces both the upper and lower ignimbrites to dull grey rocks which are not easily distinguished. Exposures showing both members are poor, and it is possible that these sheets are layers of a compound ignimbrite, such as the Waiotapu or Maraetai Ignimbrites.

Manunui Ignimbrites

The Manunui Ignimbrites (new formation) contain numerous sheets of light grey to cream vitric tuff lying above the Ahuroa and below the Rocky Hill Ignimbrites along a belt extending from the southern Hauhungaroa high country northward to Arapuni. Many of these tuffs are exceptionally well columnar-jointed, and some of the more highly welded rocks are nearly white and porcellaneous. The type locality is south of Ngapuki Road, eight miles east of Manunui (four mile sheet 9, N24/9415). Here the section is approximately 600 ft thick and contains about 15 separate sheets, mostly of fine-textured vitric tuff. Locally interbedded are thin sheets of coarser vitric-crystal tuff closely resembling that of the Whakamaru Ignimbrites in the Mangakino area. Crystal fragments in both the fine- and coarse-textured tuffs consist of plagioclase, quartz, and minor sanidine, biotite, hornblende, and hypersthene (Fig. 3).

The Manunui Ignimbrites rest on an irregular deeply weathered surface. They fill pre-existing valleys and blanket the low country around Manunui, Ongarue, and Arapuni, and also cap the Ongatiti Ignimbrite in the upper parts of the Hauhungaroa Range. These features indicate that the Manunui eruptions occurred after a prolonged pause in acid volcanism, during which much of the Pakaumanu Group ignimbrites and older sediments were eroded away. The eruptions were closely followed by major collapse of the southwestern Taupo Volcanic Zone along the eastern Hauhungaroa scarp.

Because of their structural significance and the difficulties involved in accurately dating them, these rocks deserve further study. The Manunui Ignimbrites are very similar structurally and petrographically to the Whakamaru Ignimbrites, and evidence that they are older than the Rocky Hill and Whakamaru formations is somewhat equivocal. Some field relations in the Arapuni Lake area even suggest that the Manunui tuffs may simply be fine-grained lateral equivalents of the Whakamaru Ignimbrites, and hence a facies of that formation. Similar views are held by Kear (1960) and H. R. Blank (pers. comm.) for the Manunui rocks in the Barryville area.

Rocky Hill Ignimbrites

The youngest ignimbrite formation of the western volcanic apron is made up of stratified pumice tuff-breccia unconformably overlying the Ahuroa and presumably the Manunui Ignimbrites. The tuff-breccias consist of subangular porphyritic pumice lumps up to a foot long set in a lightly welded matrix of dark grey to buff vitric-crystal tuff. One or more members of the Rocky Hill Ignimbrites (new formation) are preserved as isolated remnants scattered over the western King Country. Relatively well exposed outliers are at the trigonometric station one mile west of Aratora, and at the top of Rocky Hill, the type locality, eight miles south-east of Te Kuiti.

The ignimbrite capping Rocky Hill has a grey to yellow-grey matrix of vitric-crystal tuff containing an uncommon abundance of green hornblende (Fig. 3). This sheet also crops out two miles south-west of Arapuni. Near Te Waotu and Tokoroa it forms inliers projecting like islands above the surface of the younger Whakamaru Ignimbrites. The tuff-breccia at the base of the Marshall Ignimbrites near Mangakino may correlate with this ignimbrite.

CENTRAL AREA

General Features

In the central part of the Taupo Volcanic Zone is the well known Taupo-Rotorua Graben (Marwick and Fyfe, 1937, p. 46), a complex zone of subsidence with a tilted ignimbrite block, the Paeroa Range, in the middle. West of this complex graben area is the relatively stable Patetere or Mamaku Plateau and beyond it a second belt of subsidence, the Mangakino Basin, which forms a southern extension of the Hauraki Graben. The central and most obviously block-faulted part of the depressed Taupo Zone is referred to here as the Paeroa Graben, which is bounded on the north-west by Horohoro and the Patetere Plateau and on the south-east by the Paeroa Range (Fig. 5). The Paeroa Graben includes the smaller Guthrie and Ngakuru Grabens of Grindley (1959) and nearly coincides with the central part of the Taupo – White Island Depression recognised on geophysical evidence by Modriniak and Studt (1959).

The volcanics exposed in the central area probably cover a greater time span than those of the western apron, but exact correlations between the two groups of rocks are difficult, for only the Whakamaru and possibly the Ranginui Ignimbrites have been identified in both areas.

Paeroa Range Group

The Paeroa Range is composed largely of massive crystal-rich ignimbrites containing conspicuous biotite, quartz, and plagioclase, with minor sanidine and mafic crystals. These rocks are here designated the Paeroa Range Group, which is subdivided into the Te Kopia, Te Weta, and Paeroa formations, having a combined thickness exceeding 1500 ft. They are among the oldest

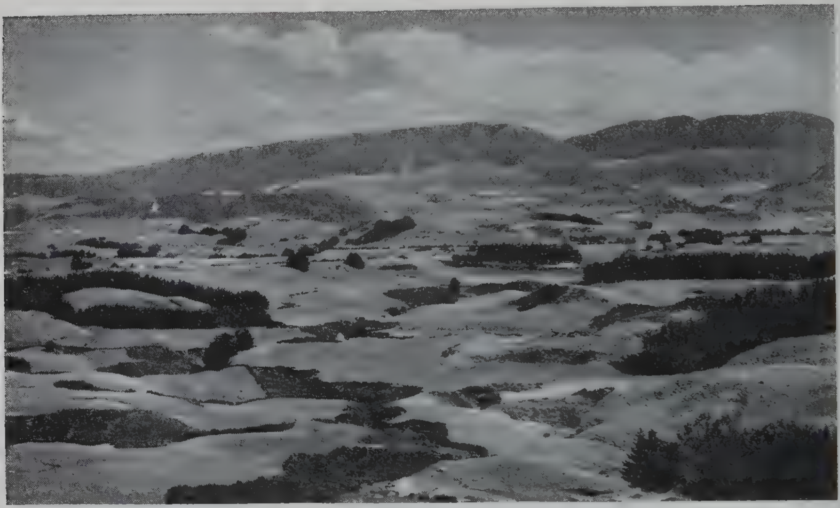

FIG. 5—General view of the Paeroa Graben looking south-east from Ngakuru Trig., near the middle of the graben. In the foreground is the smaller Ngakuru Graben, and in the middle ground are hills of the Te Weta Block of ignimbrites and younger sedimentary rocks. Along the skyline is the bordering fault scarp of the Paeroa Range, with the Te Weta and Paeroa Ignimbrites exposed on the middle and upper parts.

of the Taupo Zone ignimbrites. The type locality of the Paeroa Range Group is a section on the Paeroa Fault scarp including the type sections of the constituent formations.

Te Kopia Ignimbrites

The Te Kopia Ignimbrites form the base of the Paeroa scarp, where at least three members are exposed. The most characteristic rock type is hard, dark grey, crystal-rich welded tuff, which at places is so dense and glassy that Grange (1937, p. 64) regarded it as rhyolite. These ignimbrites have not been identified elsewhere.

As first described by Grindley (1959) the formation consists of at least three ignimbrites: a lower massive unit of hard, dark grey, lithoidal rock highly charged with crystal fragments, a middle 50-ft thick member of chaotic tuff-breccia containing rhyolite and andesite blocks up to five feet across, and an upper highly resistant member, 90 ft thick, of shiny black to brown vitrophyre having a thin crown of dark grey tuff.

One mile north-east only the lowest member is preserved. Here the very hard, dark grey rock grades upwards through lighter-coloured eutaxitic welded tuff to a fairly thick upper zone of soft white tuff. This is overlain unconformably by several sheets of similar biotitic tuff of the Paeroa Formation.

The type locality* of the Te Kopia Ignimbrites is 1·5 miles south of the junction of Te Kopia and Waikiti (Whirinaki) Valley roads (N85/736771). The base of the formation is not exposed.

Te Weta Ignimbrites (formerly part of the Ohakuri Formation of Grindley)

The high central part of the Te Weta Block (Grindley, 1959) and the steepest part of the middle Paeroa scarp are composed of buff, pumice-rich ignimbrites and subordinate sedimentary tuffs defined here as the Te Weta Ignimbrites. At the type section, just above that of the Te Kopia Ignimbrites, the base consists of soft, non-resistant tuff 75 ft thick. Overlying this is a thick series of lightly to moderately welded lithic tuff ignimbrites nearly 300 ft thick. Near the top of this series is at least one distinctive, highly welded ignimbrite consisting of crystal-rich lenticulite with irregular black lenticules up to 1·5 in. long.

Within three miles north-east of the type section, the Te Weta Ignimbrites are cut off by an unconformity below the Paeroa Ignimbrites and overlying pumiceous sediments.

Where weathered, the pumice-rich Te Weta Ignimbrites resemble the non-welded pumice tuff-breccias which overlie the Marshall Ignimbrites at Ohakuri and Ngapoipoiotore Horst, and also the hydrothermally altered pumiceous sediments overlying the Paeroa Ignimbrites on the Paeroa scarp above Waikite thermal area. These three groups of rocks are considered here to be stratigraphically distinct, but were included in a single formation, named by Grindley (1959) the *Ohakuri Formation.* Because of the different ages and lithologies of these rocks, the term *Te Weta Ignimbrites* is proposed for the pumice-rich ignimbrites of the middle Paeroa scarp and higher Te Weta Block to differentiate them from the other rocks assigned to the Ohakuri Formation.

Paeroa Ignimbrites

The Paeroa Ignimbrite was named and described by Grindley (1959) as the quartzose rocks forming the crest of the Paeroa Range and underlying the Waiotapu Ignimbrite in the Waiotapu thermal area. Included in the Paeroa Formation were other rocks, differentiated here as the Kaingaroa and Matahina Ignimbrites (Fig. 6, B). The following definition is limited to the ignimbrites of the new type section suggested by Grindley (pers. comm.) and their correlatives.

At the type locality on the crest of the Paeroa Scarp (N85/740767) the Paeroa Ignimbrites lie unconformably on the Te Weta Ignimbrites. The formation contains numerous lithologically similar sheets which are not easily traced laterally, partly because of local unconformities. They consist of light grey to buff, massive, welded tuffs containing conspicuous biotite and quartz crystals. Some differ petrographically. Those underlying the Matahina Ignimbrite on the northern end of the Paeroa scarp are texturally and mineralogically very similar to the Whakamaru Ignimbrites near

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*No type localities were defined in the brief map legend in which Grindley's (1959) new formations were described. In this paper, type localities recommended by Mr Grindley are included in the redefinitions of some of these formations, namely the Te Kopia, Paeroa, Waiotapu, Rangitaiki, and Kaingaroa Ignimbrites.

Mangakino. The ignimbrite capping the higher part of the scarp at the type section to the south is mineralogically different (Fig. 3), containing a marked dominance of biotite over the other mafic minerals, and more sanidine than any other ignimbrite examined in this study.

At the south-western end of the Paeroa scarp, in the Akatarawa Stream area, the Paeroa Ignimbrites underlie a thick sequence of tuffaceous sediments of the Huka Group. In the south-western Te Weta Block are similar overlying sediments. The Paeroa Ignimbrites have apparently been eroded from the highest part of the Te Weta Block, exposing the underlying coarser-textured Te Weta Ignimbrites.

Huka Group Volcanic Sediments and Ignimbrites

General Features

After the eruption of the Paeroa Ignimbrites, continued collapse of the central part of the Taupo Volcanic Zone created a large depression, the Huka lake basin. Here a thick sequence of juvenile pyroclastics and detrital tuffs, conglomerates, siltstone, and mudstone was deposited, together with several interbedded ignimbrites erupted during this period. Included are the Marshall, Waiotapu, Atiamuri, Matahina, and Kaingaroa Ignimbrites. These rocks partly buried the pre-existing topography of the Te Weta and Paeroa blocks.

The sediments range from fine mudstones to coarse pumice tuff-breccias containing pumice lapilli averaging one inch long. These rock types alternate as beds ranging from less than one inch to more than 30 ft in thickness. Different parts of the section appear very similar; consequently, correlation is difficult from one locality to another without the aid of distinctive and extensive marker beds.

Previous Descriptions. The first detailed work on these rocks was at Wairakei and Huka Falls, where lake sediments in the upper part of the sequence are exposed. The term *Huka Formation* was applied first by Steiner (1953) and Beck (Beck and Robertson, 1955, p. 16), and was later defined in the "Stratigraphic Lexicon" (Steiner *in* Fleming, 1959, p. 137) as the entire tuffaceous rock sequence drilled at Wairakei, approximately 2,000 ft thick, between the top of the Wairakei Ignimbrite and the base of the Wairakei (Lapilli Tuff) Breccia. The Huka Formation was subdivided by Grindley (Studt, 1957, p. 614; 1958, p. 707) into a *new* Huka Formation (Huka Mudstones) and the underlying Waiora Formation.

The term *Huka Group* was introduced by Grindley (1959) to include the Waiora Formation and Huka Mudstones and also the similar rocks of the Reporoa Basin.

Correlation of the Huka Group Beyond Wairakei. The Huka Group sediments of Wairakei were correlated northward into the Reporoa area by Grindley (1959). Further correlations with the tuffaceous rocks of the Paeroa Graben, Patetere Plateau, and Mangakino Basin are suggested here. These correlations are based largely on the presence of several ignimbrite marker beds which interfinger and extend into the sediments in these areas.

Meaning and Significance of Huka Group

The original Huka Formation of Steiner (1953; and *in* Fleming, 1959, p. 137) has been so enlarged by correlation and by inclusion of new ignimbrite formations that clarification of the new term *Huka Group* is needed.

The Huka Group is a widespread lithostratigraphic unit with type locality at Wairakei. It was probably deposited in a lacustrine sedimentary environment which persisted during a period of middle and late Pleistocene acid volcanism. The site of deposition was the Huka lake basin, formed by volcano-tectonic collapse of much of the present Taupo Volcanic Zone following earlier voluminous ignimbrite eruptions. The agents of deposition included pyroclastic flow and ash-shower eruptions of pyroclastic material, and normal stream and mudflow erosion of existing volcanic rocks.

At Wairakei the lower part of the Huka Group (*Waiora Formation*) contains abundant thick-bedded pumice tuff-breccias with minor vitric tuffs and mudstones, and the upper part (*Huka Mudstones*) contains thin-bedded buff mudstone with minor pumice tuff-breccias (Grindley, 1957, 1959; Studt, 1957, 1958). This general sequence is found also in the tuffaceous rocks at Ohakuri in the Paeroa Graben, and north-west of Mihi on the south-east flank of the Paeroa Range.

The tuff-breccias are buff, unsorted, and form massive sheets commonly 10 to 50 ft thick. Some were apparently deposited in lakes and over surrounding low country by numerous small ignimbrite or pyroclastic flow eruptions. Exceptionally large eruptions deposited the Marshall and Atiamuri Ignimbrites, which include pumice tuffs and tuff-breccias differing in colour and texture from the other rocks.

The finer-grained, thin-bedded sediments of the upper part of the sequence (Huka Mudstones) are the products of normal erosion and lacustrine sedimentation during the closing phase of ignimbrite volcanism. Generally these younger sediments of Wairakei and the Paeroa Range area are diatomaceous. In the southern part of the Taupo Zone this phase was succeeded only by minor ignimbritic eruptions such as those of the Waitahanui and Wairakei (Lapilli Tuff) Breccia.

Probably the last phase of the Huka lake sedimentation occurred in relatively small remnant lakes in the Ngakuru and Guthrie Grabens, where thin-bedded tuff and diatomite unconformably overlie more consolidated tuffaceous sediments. Slump structures and unconformities in these rocks testify to block-faulting during sedimentation, but their detailed discussion is beyond the scope of this paper.

The Huka Group at present is subdivided into a few local formations (e.g., Huka Mudstones and Waiora Formation) and contains five widespread interbedded ignimbrite formations. Complete subdivision of the group is not attempted here, but it is suggested that with more detailed mapping the most meaningful subdivision would be into formations consisting of tuffaceous sediments with a key ignimbrite horizon at the base or top, depending on the presence of unconformities below or above the ignimbrite member.

Ohakuri Formation. The term "Ohakuri Formation" was used by Grindley (1959) in mapping the tuff-breccias and fine-grained lake sediments of the Ohakuri area and similar rocks in and bordering the Paeroa Graben. No type locality was specified. Most of these rocks are hydrothermally altered and have a light brown, weathered appearance.

Superficially these rocks resemble the buff, pumice-rich ignimbrites (here called the Te Weta Ignimbrites) underlying the Paeroa Ignimbrites on the Paeroa Fault scarp. Grindley's dating of the Ohakuri Formation in the Graben as pre-Paeroa was based upon correlation with the Te Weta rocks. Distinct petrographic differences between these rocks, however, would favour their designation as separate units. The Te Weta Ignimbrites have larger crystal fragments, including sanidine and conspicuous biotite. The Ohakuri tuff-breccias of the Paeroa Graben contain smaller, less abundant crystals with little if any biotite or sanidine. They are more distinctly bedded and contain vitric tuffs and siltstones not found within the Te Weta Ignimbrites.

The Ohakuri Formation of the Paeroa Graben appears on lithologic and structural evidence to be roughly equivalent to the lower Huka Group and Mihi Breccia (Grindley, 1959) of the Reporoa Basin. It is very likely the direct correlative of the Waiora Formation, which is the main geothermal aquifer at Wairakei. Evidence for the latter correlation is the recognition of the Atiamuri Ignimbrite in the tuffaceous sediments near Ohakuri and interbedded in similar rocks beneath Wairakei, and the presence of overlying thin-bedded tuffs similar to the Huka Mudstones of Wairakei. Because of the apparent ambiguity of the term "Ohakuri Formation" and because further work on these rocks is in progress, no formal definition is proposed here.

Stratigraphic Sequence

The Huka Group sequence in the Paeroa Range area and at Wairakei is shown in Fig. 6. Column A represents the stratigraphic sequence according to Grindley (1959). Column B represents the sequence presented in this paper. Column C represents the drilled sequence at Wairakei and illustrates the approximate correlation of these and the Paeroa Graben strata.

The base of the Huka Group has been lowered in column B to include tuffaceous sediments of the Paeroa Graben area which are of similar lithology to those at Wairakei (column C) and presumed to be of the same age—that is, younger than the Rangitaiki (upper Wairakei) Ignimbrite. The top of the Huka Group has been drawn to correlate with the type section at Wairakei, but this correlation, based upon indirect stratigraphic evidence, is provisional.

The term "Mihi Breccia" (column A) is not used in column B, for no stratigraphic evidence has been found to distinguish these rocks north-west of Mihi from similar tuffaceous and pumiceous sediments of the Huka Group found elsewhere.

Marshall Ignimbrites

The oldest known ignimbrites of the Huka Group are here named the Marshall Ignimbrites, and are best exposed at the type locality in the valley extending north from Marshall's Lookout, near Mangakino (N84/210790). Here are at least four pumice-rich ignimbrite members of different degrees of welding and compaction, ranging from coarse, non-welded, pumice tuff-breccia to dense highly welded lenticulite. All except the lowest member contains fine-textured pumice inclusions set in a vitric tuff matrix containing very sparse crystal fragments, mainly plagioclase and hypersthene. They lie unconformably beneath the Whakamaru Ignimbrites and presumably rest on fine-grained tuffaceous siltstones that overlie an unnamed black and white lenticulitic ignimbrite (Fig. 4) beneath Maraetai.

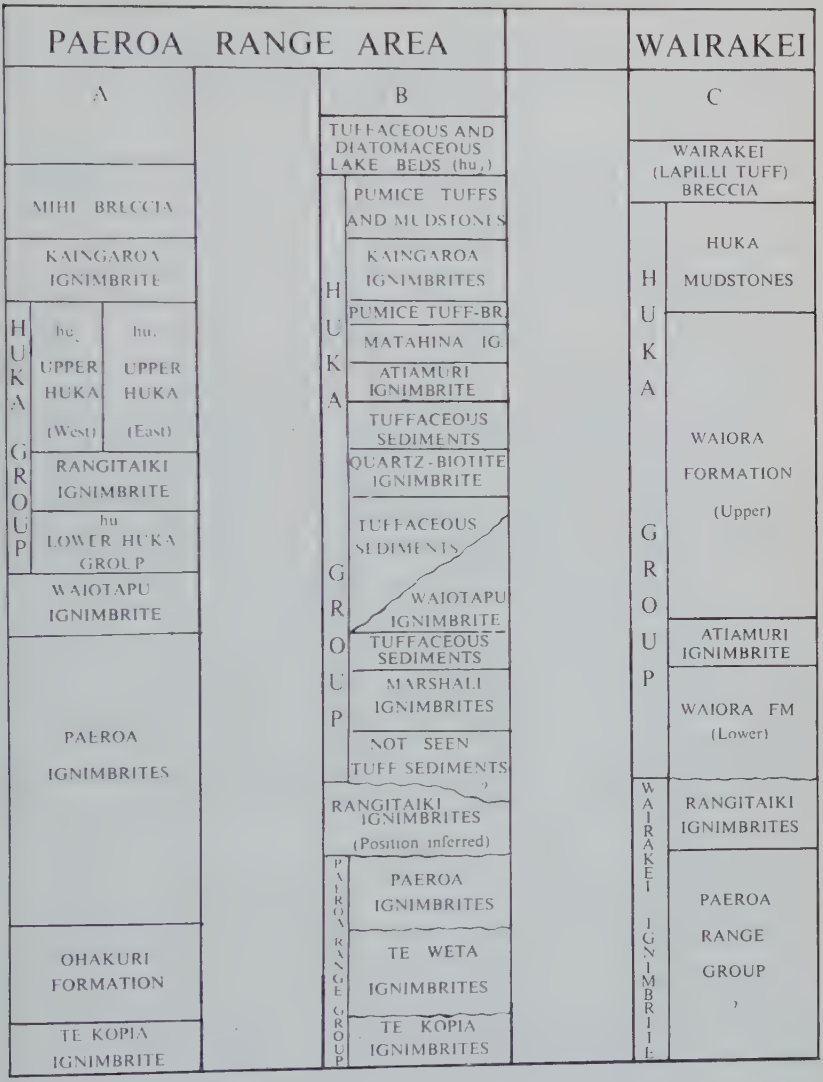

FIG. 6—Stratigraphic succession in the Paeroa Range and Wairakei areas. A. Succession of Grindley (1959). B. Succession presented in this paper. C. Drilled sequence at Wairakei, after Beck (Beck and Robertson, 1955), Grindley (1959), and Steiner (*in* Fleming, 1959, p. 137), with additions illustrating approximate age correlations with the Paeroa area rocks as indicated by the Atiamuri and older ignimbrites. Horizontal lines in this figure are approximate time lines and thicknesses are not to scale. Grindley's Ohakuri Formation and Mihi Breccia, not shown in column B, are discussed in the text.

The Marshall Ignimbrites contain a key marker bed in the central area, here named the Taupaki Ignimbrite, which consists of grey and brown lenticulitic pumice-lapilli tuff, lithologically distinct from other ignimbrites of the Taupo Zone. At the type locality the Marshall Formation contains the following members:

Member	Lithology	Approximate Thickness (ft)
Pumice tuff-breccia	Buff, non-welded pumice-lapilli tuff	150
Taupaki Ignimbrite	Grey and yellow welded pumice-lapilli tuff	75
Tuff-breccia ignimbrite	Grey tuff-breccia with pumice blocks up to 14 inches long	150+
Lenticulitic ignimbrite	Buff, highly welded pumice-vitric tuff	70

The *uppermost member,* of light buff pumice-lapilli tuff, overlies the Taupaki Ignimbrite at Taupaki trigonometric station, and also on the Te Weta block, 27 miles to the east. Angular pumice lumps are uncommonly abundant in this member, and crystal fragments are small.

Taupaki Member: This is the most extensive and lithologically distinctive of the Marshall Ignimbrites. It is best exposed near Mangakino, two-thirds of a mile north-east of Taupaki trigonometric station, as a 75-ft-thick sheet of moderately welded pumice-lapilli tuff. It is characterised by abundant yellow to orange fine-textured pumice inclusions up to 1½ in long, and smaller, less abundant, grey angular rhyolite fragments, all set in a grey vitric tuff matrix (Martin, 1959, Fig. 9A). In the upper and lower parts of the ignimbrite the pumice lapilli are non-oriented and non-deformed, but in the middle more highly welded portion they are flattened and lie sub-horizontally.

The Taupaki Member crops out along the southern and south-western margins of the Patetere Plateau, where it underlies the Waiotapu and Mamaku Ignimbrites. On the western part of the Te Weta block, four miles south of Ngakuru, it underlies tuffaceous sediments and tuff-breccias typical of those in the Paeroa Graben.

The *third member* consists of soft, poorly welded tuff-breccia with an earthy grey matrix. Texturally, it resembles the Taupaki pumice-lapilli tuff, but contains grey rather than brown pumice fragments.

The *oldest member* of the Marshall Ignimbrites is a lenticulitic ignimbrite exposed on the Waipapa-Mangakino Road, west of Taupaki trigonometric station. Here the rock grades from dense, brown, hard lenticulite near the base to non-welded pumice-lapilli tuff at the top. The "pumice" fragments are actually relicts, consisting of purplish cryptocrystalline material. Crystal fragments are very small and sparse, and its texture is generally similar to that of the less welded Taupaki member.

Waiotapu Ignimbrite

Overlying the Taupaki Ignimbrite on the Patetere Plateau and forming part of Ngapouri ridge on the opposite side of the Paeroa Graben is the very highly welded, vitric Waiotapu Ignimbrite. It consists of hard, dense lenticulite with characteristic light grey, wispy lenticules (relict pumice lumps) in a pink to light purple felsitic matrix. Plagioclase and pyroxene crystal fragments are visible in hand specimen, and traces of quartz and biotite microscopically. Its source of eruption is near Ngapouri ridge, Waiotapu, where the lenticulite grades locally into dense massive rock resembling porphyritic rhyolite, and the sheet thickens to approximately 1,000 ft.

This formation was named and described by Grindley (1959), who recognised its relatively great extent from the Patetere Plateau south of Horohoro to Waiotapu, where it dips beneath the thermal area. Marshall (1935, p. 347, pls. 67, 69) described an occurrence of this "pink wilsonite" ignimbrite near Putaruru.

The type locality is the east branch of Ngapouri ridge (N85/794767), 2·5 miles south-west of Waiotapu Hotel.

The Waiotapu formation is a compound ignimbrite. It thins westward, being 1,000 ft thick at Waiotapu, 400 ft thick south of Horohoro, and less than 60 ft thick south of Putaruru. At Waiotapu three layers are discernible as indistinct benches. Near Horohoro only two such layers are visible and near Putaruru only one. Apparently the ash flows* that deposited the Waiotapu Ignimbrite were erupted in three or more pulses, only one of which flowed westward as far as the Putaruru area.

Because of extensive erosion and partial burial by younger ignimbrites, exposures of the Waiotapu Ignimbrite on the Patetere Plateau are limited to a relatively high, narrow ridge extending north and south from Tikorangi lookout tower. Surrounding this ridge is the smooth upper surface of the Mamaku Ignimbrite, which lies unconformably on the Marshall Ignimbrites, remnants of the Waiotapu Ignimbrite, and interbedded tuffaceous sediments of the Huka Group. West of the plateau, the Waiotapu has been downfaulted in the southern extension of the Hauraki Graben and lies approximately 200 ft beneath the Tokoroa plains.

Atiamuri Ignimbrite

The Atiamuri Ignimbrite (new formation) is a sheet of poorly welded pumice-lapilli tuff resting on or within the tuffaceous "Ohakuri" sediments along the western and southern margins of the Paeroa Graben. At the type section east of the main highway, 3 miles south-east of Atiamuri (N 85/535698), it is about 45 ft thick and forms a prominent bluff. Here it rests on buff tuffaceous sediments and is overlain only by Recent ash and lapilli. At Orakei Korako, in the south-eastern part of the Paeroa Graben, it was found by Mr E. F. Lloyd (pers. comm.), associated with similar sediments. Along the edge of the Patetere Plateau, west of Horohoro, and south-east of Rotorua, the Atiamuri Ignimbrite lies between tuffaceous sediments and younger volcanic units, the uppermost of which is the Mamaku Ignimbrite.

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*The origin of the New Zealand ignimbrites by pyroclastic or ash flows is compatible with the field and petrographic evidence seen in this study. An unconventional origin from lavas composed of two immiscible liquids has recently been suggested by Steiner (1960).

Beneath Wairakei this unit lies within the Huka Group sequence. Cores have been taken at depths of 850 and 1400 ft from drillholes 32 and 33 respectively.

The Atiamuri Ignimbrite consists of buff to grey tuff, highly charged with light-brown pumice fragments and sub-round vesicular glass fragments. Its crystal composition is mainly plagioclase, quartz, magnetite, and hypersthene. Lithologically it is similar to the non-welded marginal facies of the Matahina Ignimbrite and to the Taupaki tuff of the Marshall Ignimbrites, but is distinguished from the former by its paucity of hornblende, and from the latter by the presence of quartz.

Whakamaru Ignimbrites

The term "Whakamaru Ignimbrites" was first used by Hatherton (1954) in reference to the sheets exposed along the Waikato River at the Whakamaru, Maraetai, and Waipapa dam-sites. The type section was later designated as Maraetai Gorge, Waikato River (N84/234784), by Healy (*in* Fleming, 1959, p. 476). Earlier, a petrographic description of the exposed section at Maraetai was given by Marshall (1935, pp. 347–48).

The Whakamaru Ignimbrites consist of numerous sheets of coarse-textured vitric-crystal tuff. These are among the youngest ignimbrites of the volcanic zone. They are overlain only by Recent surface deposits and possibly by the Mamaku Ignimbrite. They extend from south-western Lake Taupo to Putaruru, 55 miles north. The individual sheets are not easy to correlate, for they are similar in texture and crystal content, which includes a fairly uniform assemblage (Fig. 3) of plagioclase and quartz with minor hypersthene, sanidine, magnetite, biotite, and hornblende.

Maraetai Member. This sheet, here formally given member status, forms the lower part of the type section at Maraetai Gorge. It is a compound ignimbrite having at least three indistinct layers of different pumice content and hardness, and consists mainly of massive, grey, highly welded tuff. The compound nature of the Maraetai Ignimbrite was investigated in dam-site surveys (J. Healy, unpublished N.Z. Geological Survey reports), which led to detailed study of its magnetic properties by Hatherton in 1954. Variation in phenocryst abundance and size suggests that the Maraetai Ignimbrite, and presumably the upper Whakamaru Ignimbrites too, were erupted from the south and deposited by ash flows moving northward across the Mangakino Basin.

West of Lake Taupo are at least seven separate ignimbrites in a sequence more than 1500 ft thick. In the Maraetai-Waipapa area the Whakamaru Ignimbrites are about 800 ft thick, consisting of about ten sheets, mainly of pink and grey non-welded tuff.

Mamaku Ignimbrite

The Mamaku Ignimbrite (new formation) is one of the youngest of the major sheets of the Taupo Zone. It overlies the Huka Group sediments and the ignimbrites of the Patetere or "Mamaku" Plateau and forms a remarkably even-surfaced arch which slopes gently northward towards the Bay of Plenty. It consists of fairly distinctive, fine-textured, light blue-grey to pink, soft vitric tuff, in which the original glass shards and pumice fragments have been devitrified to soft powdery aggregates. The Mamaku Ignimbrite caps escarpments north of Horohoro, and at the south-east margin of the Mamaku Plateau unconformably overlies the Marshall and Waiotapu Ignimbrites. Its type locality is the gorge of the Mangorewa Stream at the Kaharoa-Tauranga Road bridge (N 67/646258).

On Leslie Road, east of Putaruru, the Mamaku Ignimbrite overlies tuffs which may belong to the Whakamaru Ignimbrites. A similar relation is found far to the south, between Mokai and the Ongaroto Gorge of the Waikato River.

The Mamaku Ignimbrite demonstrates well the effects of compaction in a thick ignimbrite. The familiar "tors" (Grange, 1937, Pl. III, fig. 1) of the Mamaku area west of Rotorua are butte-like residuals, characteristic of the weathered upper part of this deposit. Northward, some of the actively eroding streams such as the Mangorewa have cut through the upper portion to expose a highly welded lithoidal zone of hard, pink lenticulite 430 ft below the upper surface. Between Lake Rotoiti and the Kaituna River a thickness of 400 ft was penetrated by drilling during hydroelectric dam-site exploration (Mr B. N. Thompson, pers. comm.).

The term "Mamaku Series" has been applied to this ignimbrite and also those of the Te Kuiti area. This usage, however, is now obsolete (Thompson *in* Fleming 1959, p. 207).

EASTERN AREA

General Features

The eastern area consists of the Kaingaroa Plateau and the ignimbrite-filled valleys of the high Te Whaiti greywacke ranges to the east. According to gravity data (Modriniak and Studt, 1959) the Kaingaroa Plateau is only a partially subsided greywacke block with a relatively thin ignimbrite cover. Small inliers of basement greywacke are exposed at the eastern edge of the plateau.

Stratified volcanic rocks include the Kaingaroa Ignimbrites, the Matahina Ignimbrite, and the Rangitaiki and Te Whaiti Ignimbrites of the Waitaha Group. Older lenticulitic ignimbrites are found as cobbles of highly welded vitric lenticulite in conglomerates of early Hawera age (G. W. Grindley, pers. comm.) near Matata and Te Teko, and as isolated inliers on the eastern Kaingaroa Plateau. These are petrographically distinct from the other exposed lenticulites of the Taupo Zone. Their areal extent is unknown and they are not further described here.

Waitaha Group

The Waitaha Group, here proposed, includes the Te Whaiti and Rangitaiki Ignimbrites, which form the great bulk of volcanic rocks exposed on the Kaingaroa Plateau and the uplands to the east. These formations consist of petrographically similar, massive, grey, welded vitric and crystal tuffs, which closely resemble the Whakamaru Ignimbrites, but differ mineralogically, lacking sanidine, and containing only traces of hornblende and biotite. The Waitaha Group rests on stratified tuffs and overlaps older lenticulitic ignimbrites and Mesozoic greywacke basement rocks. It is overlain by the Matahina and Kaingaroa Ignimbrites in the northern part of the plateau. The name "Waitaha" is taken from Waitaha Forestry Road, which crosses the Rangitaiki River upstream from the contact of the Rangitaiki and Te Whaiti Formations in eastern Kaingaroa.

Outcrops of the two formations are widely spaced, and have not been found to overlap geographically (the Te Whaiti Ignimbrites occur mainly to the north, east, and south-east of the Rangitaiki Ignimbrites). Although mapping (Grindley, 1960) suggests that the Te Whaiti may be older, it is probable that they are a distal facies of the Rangitaiki Ignimbrites, produced in the same volcanic episode. The chief differences observed are that the Te Whaiti Ignimbrites are finer-textured and contain several discernible stratigraphic units, whereas the Rangitaiki Ignimbrites are coarse and composed of only one or two massive sheets. Analogous features are found in other major ignimbrite deposits, such as the Whakamaru Ignimbrites which grade into finer-textured, more discernibly stratified tuffs toward their northern margin.

Te Whaiti Ignimbrites

The Te Whaiti Ignimbrites crop out over a wide area on the north-east Kaingaroa Plateau, and fill valleys eroded in the greywacke of the Te Whaiti, Ahimanawa, and Kaimanawa Ranges. The name was chosen by L. R. Allen (unpublished N.Z. Geological Survey report) and G. W. Grindley (1960) from the Te Whaiti Valley, east of the Kaingaroa Plateau, where at least three ignimbrite sheets are exposed at different outcrops. The Te Whaiti Ignimbrites are mainly fine-textured, highly welded tuffs of vitric and vitric-crystal composition.

The type locality is at the falls near the head of the Waipunga River and the Napier-Taupo Road Bridge. Here at least four separate ignimbrites can be distinguished. They fill an ancient valley that was cut in the greywacke by a stream which once flowed westward, opposite to the present drainage direction. Crystal content of the ignimbrites increases progressively towards the base of the section. The lowest sheet is highly charged with crystal fragments and has a pronounced hackly fracture. It is exposed on the Napier-Taupo Road between Rangitaiki and the Waipunga River, and also in the Te Whaiti Valley, 25 miles to the north-east.

Murupara Member. One of the most continuous ignimbrites of this formation crops out in the area between Minginui and the Mangaharekeke Stream, and is here given member status. In the northern part of the Kaingaroa Plateau it underlies the Matahina Ignimbrite and overlies non-welded, massive sheets of biotitic tuff. The Murupara Member consists of light blue-grey, fine-textured rock resembling that of the lower Maraetai Ignimbrite at Waipapa. Its type locality is at Murupara dam site on the Rangitaiki River, six miles south of Murupara township.

Rangitaiki Ignimbrites

The Rangitaiki Ignimbrites are hard, coarse-textured, crystal-rich rocks extending as a blanket from the bluffs at Lake Rerewhakaitu southward beyond the Waimarino Stream at southern Lake Taupo. In the north-western Kaingaroa Plateau they underlie tuffaceous sediments and the Matahina and Kaingaroa Ignimbrites. The formation apparently overlies unnamed lenticulitic and other types of ignimbrites, but at the only place where the base was observed, in the Waimarino Stream valley (see Grange, 1937, p. 61), it rests unconformably on basement greywacke. The type locality suggested by Grindley (pers. comm.) is the Torepatutahi Stream gorge at the edge of the Kaingaroa scarp, Reporoa (N85/855607).

This formation was named by L. R. Allen (unpublished Geological Survey report), who mapped its full extent across the Kaingaroa Plateau and Rangitaiki Plains. Grindley (1959) later used the term "Rangitaiki Ignimbrites" in a broad sense to include all the rocks described here as the Rangitaiki, Te Whaiti, and Whakamaru Ignimbrites.

The Rangitaiki Ignimbrites consist of two members. A lower member of very dense, grey, welded crystal tuff crops out deep in the Wheao River gorge five miles south of Ngahuinga Crossing. Blocks of this ignimbrite have been ejected from a Recent explosion crater on the south side of Lake Rerewhakaitu. The upper member crops out extensively along the Rangitaiki River, Kaingaroa scarp, and the south-east shore of Lake Taupo. It consists of massive, grey, welded crystal tuff with a slightly lower crystal content that the lower member. Rounded, embayed quartz crystals, commonly $\frac{1}{4}$ in. across, are prominent, and the mafic minerals are mainly hypersthene and magnetite. One of the best exposures of this ignimbrite, at Te Toki Point, Lake Taupo, was described in detail by Marshall (1935, pp. 348–52).

Lateral variations in phenocryst size and abundance, and in the degree of welding, suggest that the upper Rangitaiki Ignimbrite was erupted from a vent about eight miles south of the site of Tauhara Volcano.

The upper Rangitaiki Ignimbrite is correlated here with the subsurface Wairakei Ignimbrite of Beck (Beck and Robertson, 1955). This correlation is mainly lithological. Surface specimens of the upper Rangitaiki Ignimbrite resemble petrographically the cores from Wairakei drillholes, and both are extremely coarse-grained and texturally distinct from any of the other Taupo Zone volcanic rocks studied. The term "Wairakei Ignimbrite" is not adopted here for this member in order to avoid confusion with the younger Wairakei Breccia or Wairakei Lapilli Tuff (Beck and Robertson, 1955; Steiner, 1953), which contains two or more sheets of tuff-breccia that are probably water-laid ignimbrites.

Stratigraphic Position. The exact stratigraphic position of the Rangitaiki Ignimbrites is not clear and has been inferred in Fig. 6B. A minimum age is suggested at Wairakei, where the upper member apparently underlies the Atiamuri Ignimbrite of the Huka Group (Fig. 6C). Their relation to the Paeroa Range Group is not known, for the Rangitaiki Ignimbrites do not crop out on the Paeroa scarp, nor have they been positively identified from drillholes in the Waiotapu thermal area. Tentatively, they are regarded as younger than the Paeroa Ignimbrites, and their absence from the Paeroa scarp and Waiotapu drillholes may be due to post-Paeroa erosion or to topographic barriers at the time of the Rangitaiki eruptions.

The "Rangitaiki Ignimbrites" indicated in Fig. 6A are coarse-textured, hydrothermally altered ignimbrites penetrated by drilling in the Waiotapu thermal area. These rocks, which overlie the Waiotapu Ignimbrite, were correlated by Grindley (1959) with the type Rangitaiki Ignimbrites of the

Rangitaiki Plains. However, core specimens examined in this study (Bore 3, depth 300 ft; Bore 4, 350 ft) are mineralogically different from the type Rangitaiki rocks, for they contain more biotite and a lower concentration of total crystal fragments. These ignimbrites are indicated in Fig. 6B as "quartz-biotite ignimbrites". They may be equivalent to the Whakamaru Ignimbrites of the Mangakino Basin area.

Matahina Ignimbrite

The Matahina Ignimbrite overlies the Waitaha Group and underlies the Kaingaroa Ignimbrites and unconsolidated pyroclastics in the northern Kaingaroa area. It is more than 300 ft thick along the lower Rangitaiki River valley, and thins westward to the Paeroa Fault scarp where it is only 50 ft thick. Here it overlies tuffaceous sediments which rest unconformably on up-arched Paeroa Ignimbrites.

Where thickest, the Matahina Ignimbrite consists of extremely hard, dense lenticulite in its welded portion, but where it thins, it grades laterally into soft, light-brown lump pumice tuff (Bailey, 1957), characterised by sparse inclusions of sub-round vesicular glass lapilli. Detailed mapping and petrographic work on the Matahina Ignimbrite by R. A. Bailey of the U.S. Geological Survey (pers. comm.) has aided stratigraphic investigations of this district by J. Healy and the writer.

The highly welded Matahina lenticulite closely resembles the lenticulite of the upper Kaingaroa Ignimbrite, found stratigraphically higher. They are distinguished, however, by the presence of quartz and hornblende which occur as tiny prisms in the Matahina, but are practically absent in the Kaingaroa Ignimbrites.

Bailey's intended type locality for this sheet (N77/263056) is expected to be flooded by the lake formed behind Matahina dam, now under construction. Tentatively, the downstream side of this dam is recommended as type locality.

Kaingaroa Ignimbrites

The Kaingaroa Ignimbrites are the youngest of the Huka Group. They include two distinct members which overlie the Matahina and Waitaha Group ignimbrites and form the smooth upper surface of the northern Kaingaroa Plateau. The upper member consists of fine-textured, pinkish, welded vitric tuff containing sparse relict pumice lenticules. The lower member consists of lightly welded, dark grey to black, pumice tuff containing light-grey pumice fragments, slightly flattened in the middle of the sheet. They are petrographically similar, containing very sparse, small crystal fragments, mainly plagioclase. Both are characterised by relatively abundant andesite fragments up to 1·5 in. long.

At the northern end of the Paeroa Fault scarp the Kaingaroa Ignimbrites overlie pumice tuff-breccias and the Matahina Ignimbrite. Relief at this locality indicates that they have been down-faulted approximately 900 ft in the graben west of the Paeroa Fault. Obviously, much of the relief in the Paeroa Graben is due to post-Kaingaroa block faulting.

In the Te Weta Block, two miles west of Te Kopia thermal area, the Kaingaroa Ignimbrites are poorly welded and interbedded with buff vitric-pumice tuffs and tuffaceous mudstone of the upper Huka Group.

Type locality of the dark grey lower Kaingaroa Ignimbrite is three miles south-east of Lake Rotowhero on the Rotorua-Murupara Road. Type locality of the pink upper Kaingaroa Ignimbrite is the quarry on Webb Road, one mile north-west of Kaingaroa Forest headquarters.

STRUCTURAL EVOLUTION

The Taupo Volcanic Zone appears generally to have evolved in the manner outlined by Williams (1941, pp. 316, 317, after Marwick and Fyfe, 1937); that is, late Tertiary upwarping of the central North Island, followed by large-scale volcanic eruptions, mainly ignimbritic, and finally, volcano-tectonic collapse to produce the complex graben features found today.

Numerous unconformities and layers of detrital sediments between the stratified ignimbrites testify, however, to a more complex volcanic history in which the above sequence was probably repeated many times. Some uncomformities, such as the post-Waiotapu–pre-Whakamaru, represent a prolonged cessation of volcanic activity during which vast quantities of rock were removed by erosion.

Ignimbrites

Structural interpretations depend largely on correlation of ignimbrite sheets. Many of the ignimbrites were deposited as 50- to 500-ft-thick sheets extending over hundreds of square miles, but because of topographic barriers few, if any, reached across the entire volcanic zone. Some of the older, more extensive formations, such as the Te Whaiti Ignimbrites, may have been deposited over the whole of the narrow southern end of the volcanic zone, but this is not certain.

The older ignimbrites crop out extensively only at the western and eastern margins of the Taupo Zone. They are mostly buried by younger rocks in the more deeply subsided central area (Fig. 4), and consequently over-all correlation is difficult.

Loci of Eruptions

The ignimbrites were erupted from widely separated vents at different times. In some ignimbrites there is a noticeable decrease in grain size, degree of welding, and thickness radially from a locus, presumed to be the eruptive vent. True ignimbrite feeder dikes have not yet been identified in New Zealand,* but using the above criteria the presumed loci of some eruptive vents (probably fissures) have been estimated within a radius of five miles or less.

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*A suspected ignimbrite feeder dike between Ongaruhe and Taumarunui was reported by Marshall (1935, p. 341; also Cotton, 1944, p. 211, and Williams, 1941, p. 317). Recent road cuttings at this locality show, however, that the so-called "dike" is merely one of many zones in a poorly welded (Manunui) ignimbrite in which the columnar jointing is askew, possibly owing to uneven cooling over an irregular basement surface closely beneath

Thus, the Upper Rangitaiki Ignimbrite was erupted from a vent several miles south or east of Tauhara, the upper Kaingaroa Ignimbrite from an area very near Kaingaroa Forest headquarters, the Ongatiti Ignimbrite from a vent near Pureora on the edge of the volcanic apron, the Waiotapu Ignimbrite from Waiotapu – Ngapouri ridge area, and the highly-welded Maraetai Member of the Whakamaru Ignimbrites from the Mokai – northern Lake Taupo area.

Volcanic Subsidence and Faulting

The major structural features of the volcanic zone have been formed by collapse related to the gigantic ignimbrite eruptions, many of which expelled more than 10 cubic miles of magma, probably within a matter of minutes. Subsidence of the whole southern and south-eastern part of the volcanic zone appears to have followed eruptions of the voluminous ignimbrites of the Waitaha Group. Further collapse of the southern area followed eruptions of the Manunui Ignimbrites, and regional warping and caldera collapse at Lake Taupo followed eruptions of the Whakamaru Ignimbrites. Many other ignimbrite eruptions farther north were probably accompanied by spasmodic collapse and block faulting that formed the Mangakino Basin and the Taupo-White Island Depression, revealed by Modriniak and Studt's 1959 and earlier gravity investigations.

Field evidence in the Paeroa Graben indicates that block faulting there has continued from at least mid-Pleistocene to Recent time, preceding and post-dating the eruption of the Kaingaroa Ignimbrites. In view of gravity evidence (Modriniak and Studt, 1959) that the deepest part of the Paeroa Graben has subsided more than 10,000 ft, the present-day fault scarps are only recent, superficial features of the larger structure. Many of the faults may have much greater displacements at depth, comparable to the Paeroa Fault, which has approximately 1,800 ft vertical slip as indicated by topography, and the Kaingaroa Fault, which has a throw of about 2,000 ft as indicated by displacement of the Rangitaiki Ignimbrites near Wairakei.

In the Taupo Zone two apparently different types of faults can be recognised. Faults of the first type have irregular or arcuate traces and their displacements are very likely normal. Examples include the faults bounding the eastern side of the Patetere Plateau and the western volcanic apron, and also the caldera-collapse faults of Lake Taupo and Lake Rotorua.

Faults of the second type have relatively straight traces and probably are normal faults with minor transcurrent components. They are best developed in the Paeroa Graben, where they bound north-east-trending grabens and horsts. Grindley (1959) interpreted these as transcurrent faults, with clockwise displacements, by analogy with the active faults of the east coast of the North Island. No direct evidence of transcurrent displacement has yet been found, however. Faults of the Paeroa Graben examined in this study are dominantly normal, and the probability of transcurrent components is suggested only by their straightness and relatively great length, which contrast with the other faults of the Taupo Volcanic Zone.

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